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The book contains abstarcts of oral and poster reports presented at the 14th International Conference "Gas Discharge Plasmas and Their Applications" (GDP 2019). This event is a continuation of conferences on gas discharge physics held in Russia since 1984, as well as seminars and conferences on the technological application of low-temperature plasma. The conference is held every 2 years in different cities of the Russian Federation. This year, the wonderful Siberian city of Tomsk, known for its intellectual environment, was chosen as the venue. The program of the Conference covers a wide range of technical areas and modern aspects of the physical processes occurring in generators of low-temperature plasma, low and high-pressure discharges, pulsed plasma sources, surface modification, and other gas-discharge technologies.

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NANO-, SUBNANO-, AND PICOSECOND PROCESSES IN HIGH-POWER ELECTRICAL DISCHARGES IN GASES[1]

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Electrical discharges in gases are of great importance in pulsed power devices, such as gas lasers, in pulsed light sources, in production of short-term electric and magnetic fields, etc. To solve many problems in these areas, it is necessary to have switch-on times in the range 10^{-12}–10^{-9} s [1]. Such short times can be achieved by utilizing discharges of four types, namely (I) high-pressure gas discharges operating under static breakdown conditions, (II) discharges operating under the conditions of a relatively low overvoltage ($\Delta \leq 3$) and ultraviolet initiation, (III) discharges initiated by an accelerated electron beam injected directly into the gas, and (IV) pulsed discharges in highly overvolted gaps. In experimental studies of all these types of discharge, a charged coaxial line is discharged into a two-electrode spark gap with a uniform electric field between the electrodes.

In studying the discharge under static breakdown conditions [2], the breakdown voltage is given by $U_s = F(pd)$ (Paschen's law), where p is the gas pressure and d the gap spacing. It was assumed that the conductivity of the gas-discharge plasma is proportional to its specific energy. In terms of this model, the current switch-on time can be estimated from the formula $p\tau = a(E/p)^{-2}$, where E is the electric field in the gap and a is a constant characterizing the gas. We have shown that this formula holds for air and nitrogen at $\tau \approx 10^{-10}$–10^{-9} s.

For pulsed discharges initiated in gaps with $d \leq 1$ cm and overvoltage $\Delta = U_s/U \leq 3$ by means of ultraviolet irradiation, we obtained that the switch-on time can be estimated as $\tau = A(\alpha v)^{-1}$ [3], where α and v are the impact ionization coefficient and the electron drift velocity, respectively; $A \approx 10$ for air. This formula was derived assuming multi-avalanche multiplication of the initiating electrons. The experimentally obtained time τ for atmospheric air at $\Delta = 3$ was $5 \cdot 10^{-10}$ s.

We have demonstrated that with direct injection of electrons into the gas, it is possible to obtain a discharge in a large volume with the switching time as short as and even shorter than 10^{-9} s due to the gas ionization by electron beam.

At high overvoltages, $\Delta \geq 10$, the electric field is so high that the electron runaway effect arises (for nitrogen and air, at $E/p \geq 600$ V/cm·Torr). We have shown that the duration of runaway electron pulses is 10^{-12}–10^{-11} s [4]. In this case, the runaway electron beam plays the same part in the discharge initiation as the externally injected electrons. The switch-on time with participation of runaway electrons lasts for ~10^{-10} s. It has been demonstrated that discharges of this type also operate in a multi-avalanche mode.

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LOW-PRESSURE PULSED GAS DISCHARGES WITH HOLLOW CATHODE AND HOLLOW ANODE AND THEIR APPLICATIONS*

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This review deals with the fundamental properties of the low-pressure gas discharges with hollow cathode and hollow anode. The conditions of low pressures imply that the electron free path for ionization exceeds a characteristic size of the interelectrode gap. Then the discharge keeps an intermediate position between the classical glow discharge with an avalanche ionization and a pure vacuum discharge that burns in the cathode material vapor [1–3].

The single electrons appearing at the cathode surface cannot initiate the low-pressure discharge. The principal idea for interpretation of the discharge initiation mechanism is reduced to the following. At the stage of delay time to breakdown, a considerable electron current from the cathode is required. In spite of the fact that only a small fraction of the electrons enters into reaction of ionization, the excess space charge of positive ions builds up in the gap with time. As a result, the electric field is distorted in such a manner that the potential distribution along the discharge axis is no longer monotonic. A region of potential hump forms near the anode so that the electrons oscillating in this region assure the intense gas ionization and formation of the plasma column. This mechanism is confirmed for a wide interval of gas pressures. For example, when the pressure is at a level of 10^{-2} Torr a typical gap distance amounts to about 1 cm. On the other hand, the characteristic size of the gap can be increased to about 100 cm when the pressure decreases to 10^{-4} Torr.

A great interest to the discharges under discussion is associated with their applications. One of the fields of application is related to specific type of discharge with extremely high total current and respectively with extremely high current density. Similar systems are used in a novel type of the high-current switching devices often named the grounded-grid thyratrons or pseudospark switches [2, 3]. At the current time, these thyratrons are used for parallel switching with nanosecond stability of a large number of devices in the linear electron accelerators [4, 5]. The state of art as applied to this problem is mainly considered in the present paper.

The other field of application is related to generation of a uniform plasma in a large volume of the cathode or anode cavity. Such discharges are often used for surface modification, when the samples are immersed in plasma. The discharges with hollow anode constitute the basis for the sources of the charged particles with plasma emitter. The method of extraction of the particles from plasma allows obtaining the high-energy electron or ion beams with a large cross section. This directions of application is also partly considered in the review.

One of the conclusions of the paper is that the mechanisms of the discharge initiating and sustaining turn out to be general in spite of the seemingly different conditions of the discharge burning.

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ELECTRON BEAM EXCITED PLASMA AND BEAM PLASMA DISCHARGE IN PLASMA PROCESSING TECHNOLOGIES *

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The report addressed the following issues:

History of discovery, research and applications of a beam-plasma discharge (non-relativistic and relativistic plasma electronics; active geophysical experiments; plasma processing technologies).

The physical mechanism of discharge, the main characteristics, features of manifestation at qualitatively different external conditions.

Principles of non-equilibrium plasma chemistry.

Electron beam excited Plasma (EBEP): physics, basic characteristics, LAPPS installation, applications for nanoelectronics.

Beam plasma discharge with a plasma cathode: main characteristics; technological applications.

Beam-plasma reactor of FIRE RAS: design; features of operation in the presence and in the absence of a magnetic field.

Computer modeling of processes in the reactor of FIRE RAS: features of the development of beam instability in a plasma resonator; energetic parameters; ion distribution function.

BPR reactor applications:

Low energy etching of materials and structures for nanoelectronics.

Deposition of nanoscale carbon films.

Restructuring of carbon films, obtaining graphene.

Prospects for the development of BPR reactor.

* This work was supported partially by RFBR (grants ##14-08-143, 18-29-19047, 19-07-00432)

ATMOSPHERIC PRESSURE PLASMAS TREATMENT OF AL_2O_3-FILLED EPOXY RESIN FOR ACCELERATING SURFACE CHARGE DISSIPATION *

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Al_2O_3-filled epoxy resin (Al_2O_3-filled Epoxy Resin) is widely used as an insulating material in electric power and pulsed power systems. Investigations on its surface characteristics, especially the surface insulating property are continuing hotspots in high voltage engineering [1-2]. In this paper, plasma etching and plasma deposition were used for the modification of the Al_2O_3-ER surface at atmospheric pressure. The evaluation comparison of surface charge dissipation was compared. The experimental results showed that both treatments could suppress the surface charge on the Al_2O_3-ER surface. The maximum surface potentials after plasma etching and plasma etching decreased to 60.09% and 23.37%, respectively, compared to that of the untreated sample. The decay rates of the surface charges on the DBD deposited exceeded 98%, while the decay rates were 35.91% and 0.75% on the plasma etched and untreated samples (Figure 1). Surface morphology illustrated that the surface roughness of the plasma deposited sample was smaller than the of the plasma etched sample. A flat surface improved the uniformity of electric field, thereby reducing the surface charge accumulation. The surface conductivity after plasma deposition increased three orders of magnitude higher than that of the untreated sample, which effectively improved the surface charge dissipation on the Al_2O_3-ER surface. Ageing effects of the both treatments were evaluated. Results showed that there were no obvious ageing effects after plasma deposition, making a stable surface charge dissipation in five-day storage. However, the plasma etched samples showed a significant ageing effect because the oxygen-containing functional groups introduced after plasma etching reoriented towards the interface when the ageing time increased.

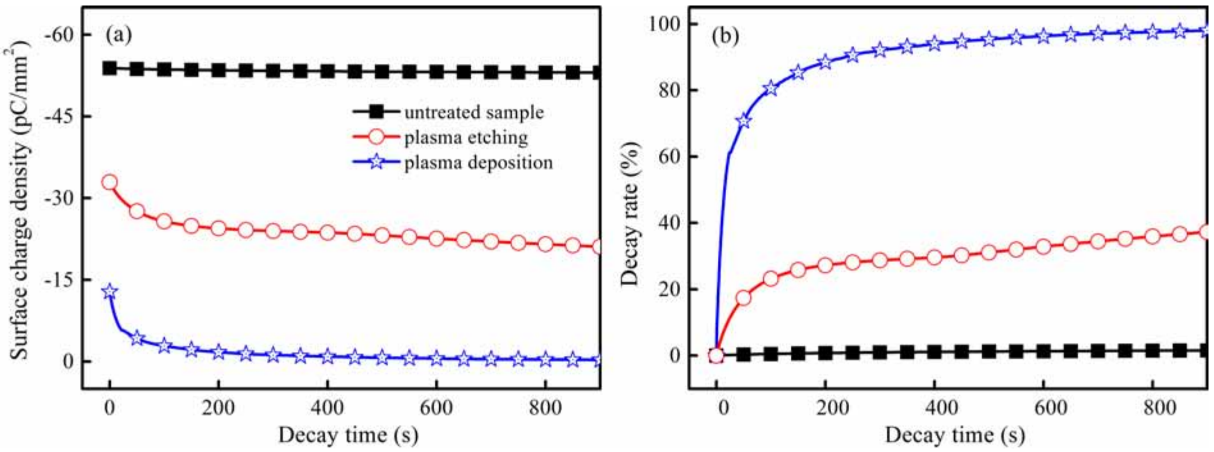

Fig. 1. The dependence of surface charge density and the decay rate on the decay time

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INTERACTION OF COLD ATMOSPHERIC PLASMA JET WITH DIELECTRIC TARGET*

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Non-thermal atmospheric plasma jets are powerful instruments successfully used for different applications in medicine, agriculture and material surface manufacturing. Streamers originated near the powered electrode in a dielectric tube of plasma device propagate over an inert gas jet to a treated target. The streamers deliver to the surface the high density plasma, high electric field, surface bombardment by ions and initiate chemical reactions in the mixture of nitrogen, oxygen, water. Plasma devices generating a sequence of streamers over an inert gas jet in ambient air are recently widely used in anticancer therapy. An enhancement of electric field carried by the streamers to the target surface is a way to intensify the plasma jet impact on a cell life cycle.

In this work, in the experiment and in numerical simulations we study of the dynamics of plasma jet, plasma chemistry over a zone of plasma-target contact and the interaction with the cancer cells in vitro. The calculated spatial distribution of electric field and electron temperature are input parameters for plasma enhanced chemical model in a mixture of He/Ar and ambient air (N2, O2, H2O). The calculated optical spectra are compared with measured ones over a range of wavelength 250–750 nm. The dynamics of the streamer propagation over helium and argon is compared in the experiment and 2D fluid model simulations with the model developed in Ref. [1]. The electric field penetration in cancer cells covered by water layer is calculated. Two stages of the ionization process induced by the streamer near the plasma-target interface are observed in the experiment and simulations. The first stage is related to the streamer approaching the surface and lasts 100-200 ns. The second stage is the stationary self-sustained ionization and lasts much longer during a positive cycle of sinusoidal voltage applied to the electrode inside of the plasma device.

The viability of cancer cells plated in 96 well with flat-bottom plates is studied and compared for different regime of plasma jet generation.

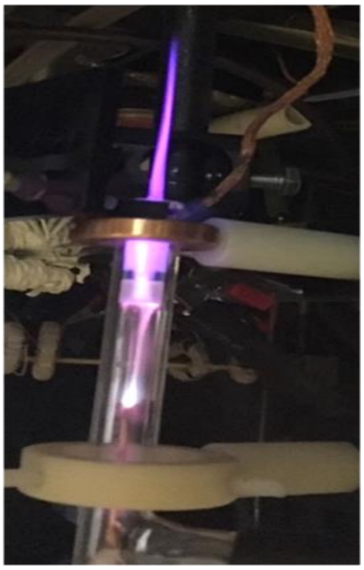

Fig. 1. Photo of experimental setup

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OES DIAGNOSTICS OF PLASMA OF FAST DISCHARGES IN STRONGLY OVERVOLTAGED GAPS*

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Due to its unique properties, non-equilibrium low-temperature plasma (NLTP) is widely used in various fields [1]. Currently, one of the most promising objects is dense NLTP. One of the most reliable ways to create such a plasma is a diffuse discharge realized as a result of applying high-voltage pulses of both polarities with a rise rate of 10^{13}–10^{15} V/s to gaps filled with high-pressure gases and providing strong overvoltage [2]. From the point of view of the practical use of any plasma object, it is extremely important to know its basic parameters (electron concentration N_e and temperature T_e; vibrational T_v, rotational T_r and gas T_{tr} temperatures; reduced electric field strength E/N). However, it should be noted that due to the strong non-equilibrium of such a plasma, classical techniques are indispensable for its diagnosis. This study presents the results of applying some methods of optical emission spectroscopy (OES), suitable for diagnostics of plasma, obeying the radiational-collisional model. In the experiments, NLTP plasma was formed in "point-plane" gaps filled with dense gases (helium, air, nitrogen, argon). Optical signals from the plasma passing through a monochromator were recorded with detectors providing spectral and temporal resolution up to ~0.2 Å and ~100 ps, respectively. Using the method based on measuring a spectral distance $\Delta\lambda$ between the forbidden (447.0 nm) and the allowed (447.15 nm) components of the atomic helium line (Fig. 1a) and giving reliable results in the range 10^{14}–10^{16} cm^{-3} [3], N_e in diffuse discharge plasma was measured. Thus, for NLTP in pure helium at a pressures of 0.5–4 atm, the average values of N_e are ~10^{14}–10^{15} cm^{-3}. This result is in good agreement with that obtained with Stark method [4]. To determine T_e and E/N, we used the method based on measuring the ratio $R_{391/394}$ of the peak intensities of the ionic (391.4 nm) and molecular (394.3 nm) nitrogen bands [5]. Using the measuring complex, the time behavior of the intensities of mentioned bands in the discharge plasma of atmospheric-pressure nitrogen at different distances L from the potential pointed electrode along the longitudinal axis of the discharge gap was recorded. There are dependencies of T_e and E/N on L for one of the moments at the breakdown stage in Fig. 1b,c. However, it is worth pointing out that these data refer to the time instants when the radiation intensity is sufficient for recording. At an earlier stage, these values should be even higher. Then they decrease rapidly. The non-uniformity of the values along the gap is explained by an increase in the electric field near the electrodes. In addition, using these data we estimate the average velocity of the streamer (ionization wave) providing gap breakdown. It is ~10^9 cm/s. These experimental data are in good agreement with the results of simulations [6].

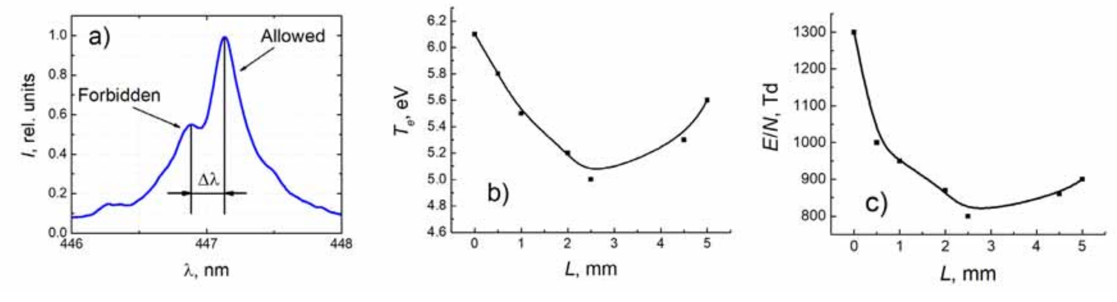

Fig. 1. a) Spectral line of He I (447 nm). b, c) Dependencies of T_e and E/N on L. N_2, 1 atm. Gap width is 5 mm.

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INTERACTION OF HIGH-DENSITY CATHODE-SPOT PLASMA WITH A MAGNETIC FIELD*

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Vacuum electrical discharge implies the plasma production from the electrode material [1]. The current transfer over that plasma occurs with electron emission from the cathode accompanied by the plasma production. It is commonly accepted that the emission and plasma production from the cathode occurs in pulsed-periodic manner, similarly to the boiling. The key features of the single pulse arises from the explosive-electron emission (EEE) event occurring in the micro volume within nanoseconds due to the Joule overheating of the emission region. The current pulse producing by the EEE – ecton being accompanied by the metal explosive plasma expanding outward the emission micro region at the cathode at velocities reaching 5 – 20 km/s. The ensemble of the pulsed-periodically occurring EEE cells forms the cathode spot.

As there is an ignition of new EEE cells instead of the preceding ones, there is an apparent motion of the spot. With the magnetic field applied to the vacuum arc discharge its cathode spot exhibit so-called “retrograde” motion that is average drift motion in anti-amperian direction, **B**×**I**.

It has been shown that for the EEE-cell plasma the general parameters [2]

$$\beta = \frac{4m_e c^2}{e^2}\frac{1}{\kappa^2 n R^2} \qquad\qquad \omega\tau = \sqrt{\frac{2}{\pi}}\,\frac{\kappa}{m_e c^2 e^2}\,\frac{T_e^2}{\Lambda}R \tag{3}$$

(with $n > 10^{18}$ cm^{-3}, radius $R < 10$ μm, $T_e \sim 1$ eV, Coulomb logarithm $\Lambda \sim 1$, and $\kappa = j\sqrt{\frac{2\pi m_e}{T_e}}/en < 1$), correspond to the range $\omega\tau << 1 << \beta$. This implies that the self-magnetic field of an EEE cell has no influence on the dynamics of its plasma. However, new cells may arise some distance away from the preceding ones. For this case, it is necessary to take account of the decrease in plasma density and in magnetic field with distance. For the density decrease nr^α = const (with $\alpha = 2$ and 3) one may obtain that

$$\omega\tau = \varpi\frac{r^\alpha}{n_0 r_0^\alpha}\left(\frac{2I}{cr} + B_e\cos\varphi\right), \qquad \varpi \equiv \frac{e}{mc}\frac{\sqrt{m}T^{3/2}}{\pi\Lambda e^4}, \tag{26}$$

reaches 1 at about 10 μm, where unperturbed density is high-enough to ignite new EEE-cells.

Using the MHD equation for the plasma velocity v_{pl} perturbed by an external magnetic field

$$M\frac{dv_{pl}}{dt} = Mv_{pl}\frac{dv_{pl}}{dr} \approx -T\nabla\ln n - \frac{1}{c}\frac{\omega\tau}{1+\omega^2\tau^2}Ze(v_{pl}+v_{1e})\left(\frac{2I}{cr} + B_e\cos\varphi\right). \tag{28}$$

(where $v_{1e} \sim (T_e/M_i)^{1/2}$ is the electron drift (current) velocity [2]) for $\omega\tau < 1$ and the continuity equation in it its simple form of a flux conservation law nv = const, one may estimate perturbed plasma density distribution, and corresponding “velocity” of apparent retrograde motion of a cathode spot [3]:

$$v_{retr}\frac{\tau_{ign}}{R} = \left[\frac{v_{1e}}{T(1+\alpha\ln R/r_0)} + \frac{1}{\sqrt{2MT(1+\alpha\ln R/r_0)}}\right]\frac{Z}{mc^2}\frac{\sqrt{m}T^{3/2}}{\pi\Lambda e^2}\frac{R^\alpha}{n_0 r_0^\alpha}\frac{8}{\alpha c}I\,B_e \tag{33}$$

that increases both with I and B. The estimated values of v_{retr}/B_e ranging from a few to tens of m/(s T)

$$v_{retr} \sim \frac{R}{\tau_{ign}}\times 10^{\alpha-6}\,I\,B_e\ \mathrm{T^{-1}A^{-1}}. \tag{36}$$

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RAILGUN GAS SWITCHES IN OSCILLATORY REGIME OF DISCHARGE*

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Discharge of a capacitive storage on a load with unipolar pulse is employed for pumping of powerful lasers and also for feeding of electromagnetic launchers, and pulsed high magnetic field facilities. Spark gaps are often used to commute energy on a load. Triggered spark gaps with electrodynamical acceleration of spark channel were developed and investigated by Kovalchuk and colleagues for the unipolar pulse mode [1-3]. In some applications oscillatory regime (underdamped sinusoidal) has to be realized for the capacitor bank discharge. In particular, it is valid for a pulsed electromagnetic forming (EMF) technology, which is used for assembling welding, cutting, and forming the details of products in various branches of industry [4]. Spark gaps, developed for unipolar discharge, cannot directly be employed in under-damped (oscillatory) regime, because at current transition through zero the arc channel could stop motion and ignite at initial place on the following half period. This phenomenon was observed by investigating the moving spark behavior [5] in the coaxial rotary switch. The conclusion drawn in [5] is that the re-ignition points are dependent on the magnitudes of the current; it is shown that for the lowest current, the point of re-ignition is close to the point of first ignition, but as the spark current increases, re-ignition after zero-crossing of the current is initiated at the same point at which the spark was extinguished. Compact gas switch, intended for operation in oscillatory (low damping) regime of discharge, was introduced in [6]. It is a two-electrode switch with electrodynamic acceleration of a spark channel in planar geometry. New geometry of coaxial switch with closed loop rotating arc has been implemented and investigated in this paper. Different operations regimes have been investigated with wide variation in the current-voltage amplitudes and pulse duration (up to 3 ms). Moreover, arc motion was investigated by use of optical and electrical probes depending on the current and charge transfer and compared with simulations.

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EXPERIMENTAL ESTABLISHING OF PLASMA OPENING SWITCH VOLTAGE SCALING

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It is theoretically generalized how the plasma opening switch voltage scaling depends on conduction current [1]. The scaling experimental verification with the megaampere installation GIT-4 is presented. It is found that the peak switch voltage dependence on the conduction current has a nonmonotonic profile: a part of the voltage increase at the switch conduction current less than ~1 MA is replaced by the voltage decrease at the further increasing of the current to the level more than ~1 MA. The change in scaling is due to a different mechanism of magnetic field penetration through plasma: the switch operation regime with plasma erosion dispersal is replaced by the regime of plasma aggregation under the strong magnetic field pressure [2]. As a result, the pulse power arising on current interruption is restricted by the peak voltage reached at the switch current of ~1 MA. The detected switch voltage scaling is also confirmed by the approximation of the experimental data obtained with the megaampere facilities HAWK [3] and DECADE [4].

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ON THE NATURE OF CHARGED PARTICLE FLOW IN VACUUM ARC*

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Time resolving investigations of charged particles flows from the cathode region of the vacuum arc reveal that the basis of charged particles flow is short -term bursts[1]. These bursts can form sequences of bursts, groups of bursts with a relatively smooth waveform and superbursts. The Fourier analysis shown that ion flow has a brown-like frequency law. This fact can serve as the evidence of fractal nature of the cathode spot[2]. However, the detailed analysis of ion and accelerated electron signals revealed that the fractal nature of charged particle signal can reflect the fractal nature of plasma turbulences in discharge plasma. The wavelet analysis of shows the self-similarity in ion flow time dependence (Fig.1).

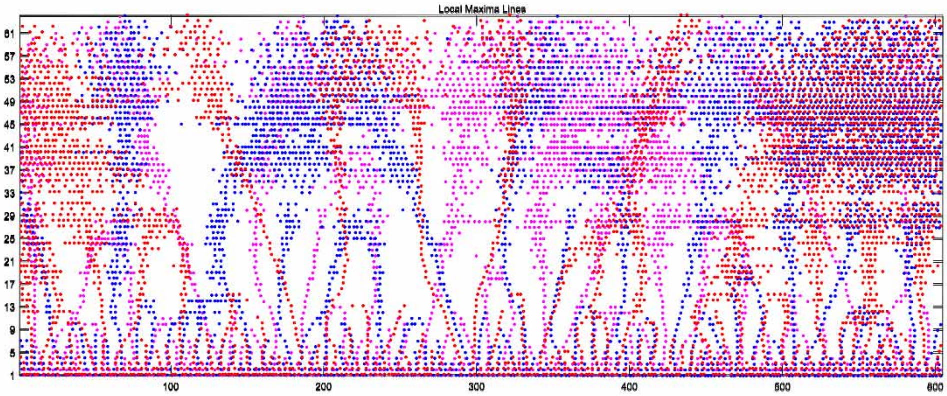

Fig. 1. The "skeleton" picture of wavelet spectrum of ion flow from vacuum arc with copper electrodes

Also, the strong correlation between intensive charged particle flow appearance and arc discharge parameter instabilities was revealed. Thus, the plasma instabilities can be considered as the cause of ion and electron flow acceleration in the vacuum arc.

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STUDY OF THE ION PLASMA FLOW GENERATED BY VACUUM FLASHOVER DISCHARGE*

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The pulsed vacuum flashover discharge is widely studied but most works are connected with pre-breakdown and breakdown phenomena [1]. The results of the plasma ion flow study for different pulsed discharge parameters using small-sized ion detectors are presented in this paper.

A coaxial plasma source was used. The cathode was made of copper wire with a diameter of 1 mm, the anode ring was made of brass with a diameter of 4 mm. Cathode–anode gap was 1 mm. A cable generator with amplitude from 10 to 30 kV and pulse duration from 18 to 100 ns were used as a source of high-voltage pulses. All studies were carried out at a pressure of 10^{-5} mm Hg.

Compact ion collectors were used to study the parameters of the ion flux and electron current. To determine the spatial and temporal structure of the flow, the analyzers were installed at various angles from 0° to 60°. It was assumed that the ion flow from 60° to 90° degrees is insignificant. The analyzer has an inlet 10mm diameter, with 50µm net. The particle collector is made in the form of a copper spiral. When measuring the flow of electrons, an additional retarding grid was installed in front of the collector. To analyze the distribution of electrons, a negative potential from 0 to –90 V was applied to the retarding grid. For each combination of parameters, an averaged waveform was obtained. It was also carried out numerical integration over the angles to calculate the total ion current.

Typical ion density diagram is presented at Fig. 1. The main ion flow reaches the detector in 1.5 µs. Almost all ionic current is distributed in solid angle up to 60°. The maximum current density is achieved at an angle of 15°.

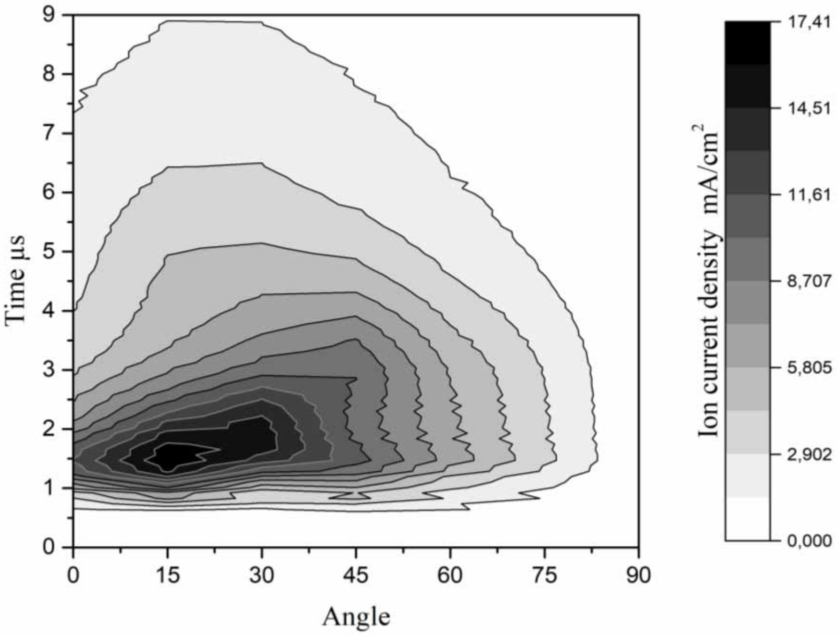

Fig. 1. Ion current density as a function of angle and time. Discharge duration 45ns, pulse amplitude 20kV.

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INVESTIGATION OF ELECTRON TRANSITION INTO RUNAWAY MODE IN INHOMOGENEOUS ELECTRIC FIELD IN VARIOUS GAS MEDIA*

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Transition of field-emitted electrons into the runaway mode is investigated in the region of enhanced electric field determined by the configuration of a microtip on a cathode for various gas media composition and pressure. The research is done using simulation of electron motion in the inhomogeneous electric field with a help of the Monte-Carlo procedure in the 3D configuration. Calculations were carried out for nitrogen, hydrogen and CO2:He:N2-mixture (1:1:3). It's shown that passage through a relatively small region of the enhanced field in the vicinity of the microtip may substantially facilitate electron transition to the runaway mode. This effect enhances at pressures of greater than 10 atm. In our opinion, the resulting runaway electrons may provide preionization of gas medium and formation of the initial stage of a volume discharge. The results obtained are of interest for studies of the switching properties of ultrahigh pressure gaps and the use of a volume discharge for lasers pumping.

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CURRENT-VOLTAGE CHARACTERISTICS OF THE HIGH-FREQUENCY ARC DISCHARGE IN THE AIR.

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The paper considers the results of a theoretical and experimental study of a high-frequency arc discharge [1] in air at pressures above atmospheric. The model of this type of discharge allowed the calculation of current-voltage characteristics and the energy balance of the high-frequency arc, depending on the geometrical dimensions of the discharge chamber of the plasma torch for different pressures and flow rates of the plasma gas.

The main dependences obtained by theoretical analysis of the high-frequency arc discharge are current-voltage and current-temperature characteristics of the discharge. Due to the used theoretical model, the calculated characteristics are applicable not only to the high-frequency arc, but also to high-voltage low-current arcs of direct current.

The calculated current-voltage characteristics have a falling character. In this case, the degree of inclination changes insignificantly with changes in pressure and gas flow rate, length of the discharge gap, and diameter of the discharge tube.

An important feature of the arc discharge in air is the appearance of overheating instability associated with the non-monotonic dependence of the thermal conductivity of air on temperature. The non-monotonous nature of thermal conductivity is associated with the dissociation of nitrogen and oxygen molecules and has two peaks: in the temperature range (3500-4500) K and (7000-10000) K. The position of the peaks depends on pressure. With its increase, the peaks are shifted toward higher temperatures. As a result of overheating instability, current surges and plasma temperatures appear, and loop-shaped sections appear on the current-voltage characteristics of the arc.

Overheating instability was confirmed by an experimental study of the high-frequency arc discharge. The current jumps were accompanied by a sharp rise in plasma temperature and radiation from the discharge region. The active power of the discharge increased, but the reactive power of the discharge increased especially strongly. This is due to both an increase in current and discharge inductance caused by a decrease in the radius of the conductive zone.

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INVESTIGATION OF THE EXPANSION DYNAMICS OF THE NEAR-SURFACE LIGHT EROSION PLASMA FORMED DURING THE EVAPORATION OF A MATERIAL BY BROADBAND HIGH-BRIGHTNESS RADIATION *

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The dynamics of the vapor-plasma flows formed at impact of magnetoplasma compressor (MPC) [1] – [3] discharge radiation on targets of various materials with use of methods of a holographic interferometry and schlieren photos is investigated.

The interaction of powerful broadband radiation with matter accompanies the processes on the walls of fusion reactors [4], [5], the ablation of heat-shielding layers of aircraft [6], the processes in plasma accelerators and electrodynamic devices [1], [7], in technological (photolithography, radiation hardening of the surface) and photochemical processes [8] – [11]. This explains the interest in these studies.

The MPC discharge in gases (Ne, Ar) was used as a radiation source. The total energy input to the discharge was up to 3.2 kJ, of which 40% was in the first half-cycle of current, the current maximum reached 160 kA, the half-cycle time was 6 μs. The discharge radiation energy was 1 - 1.5 kJ [2, 3], at the same time in the vacuum ultra-violet spectral range (photon energy $h\nu$ more than 6 eV) were radiated about 50% in Ar ($h\nu$ up to 16 eV) and 70% in Ne ($h\nu$ up to 21 eV). Targets were made of Al, Cu, Ti, Pb, C, PFTE in the form of bars with dimensions of 30 mm by 50 mm and a thickness of 10 mm and were set the long side along the discharge at a distance of 45 mm from the MPC axis. Also we used a PTFE target "witness", wich was mounted symmetrically to investigation samples relative to the discharge axis. The diagnostics of gas-dynamic processes over the targets was carried out using Schlieren-scheme and the method of two-exposure laser holographic interferometry with temporal and spatial resolution 10 ns and 50 μm, respectively.

In the schlieren and interferogram photos, zones characteristic of the studied process radiation with matter interaction are well visible: the gas-dynamic evaporation mode is realized (plasma piston mode), there is a shock wave in the gas, the contact boundary between the shock-compressed gas and the vapor plasma. The interferograms analysis indicates that the regime of developed evaporation is preceded by a regime of diffusion evaporation. On the interferograms above the targets at different distances from the radiation source (from the MPC), we observe 3 types of gas-dynamic perturbations: an acoustic wave, a simple wave (Riemann wave), and a shock wave. Qualitative and quantitative description of processes in these zones is discussed in the report.

The effect of the radiation spectral composition (the method of gas spectral cutoff of VUV radiation), the targets materials, and the degree of surface treatment on the evaporation is shown experimentally

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MEASUREMENT OF PLASMA PARAMETERS IN AN ELECTRON SOURCE WITH A PLASMA CATHODE BASED ON A LOW PRESSURE ARC DISCHARGE*

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In electron sources with a plasma cathode, the beam parameters (current amplitude, duration and frequency pulses) are controlled by a corresponding change in the parameters of the emission plasma [1,2]. In this regard, it is necessary to investigate the processes occurring in the plasma cathode, which ultimately determine the stability of the electron source as a whole.

In this work, in a source of electrons with a grid plasma cathode based on a low-pressure arc discharge, parameters of the emission plasma were investigated depending on various conditions of its generation, for which a cylindrical Langmuir probe of 0.3 mm diameter and 5 mm length was used. To measure the current-voltage characteristics (CVC) of the probe, taking into account the peculiarities of the functioning of the electron source (galvanic isolation from high accelerating voltage, the use of high-voltage cables with high parasitic parameters, etc.), we used the scheme shown in Fig.1. To eliminate the influence of parasitic parameters, the measurement circuit was located in the maximum proximity to the plasma generation space in the vacuum chamber. Measurement of the probe CVC was carried out using a microcontroller (MC) (voltage and current of the probe at resistances R_2 and R_{sh}, respectively). Data transmission from the vacuum side was carried out in a digital code in a pause between the generation of discharge current pulses through the conductors of a high-voltage cable that supplies power to MC a 3.5V. The receiving MC, the 3.5 V power supply and the source of the pulse potential bias of the probe were located in the high-voltage electrostatic shield from the atmospheric side. Then the data was transferred to a computer using fiber-optic communication channels.

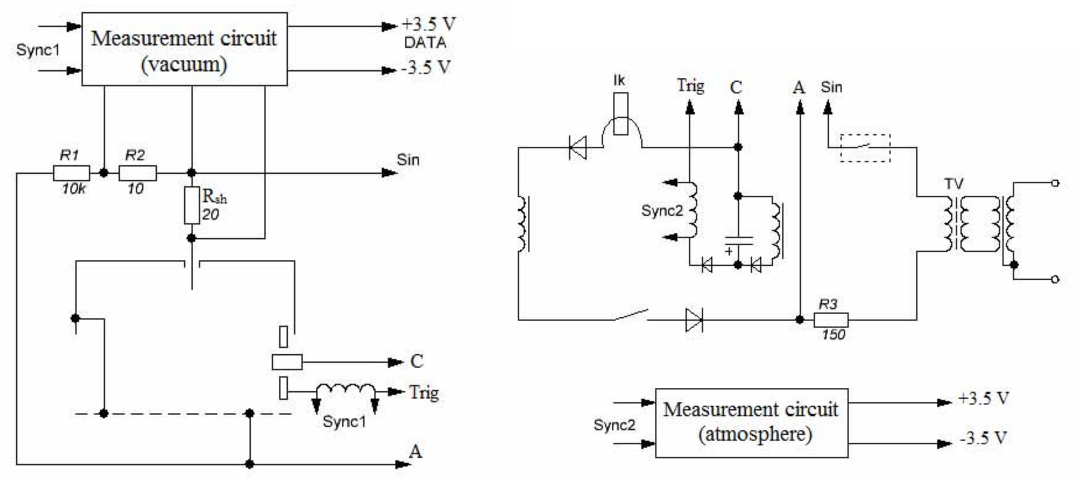

Fig. 1. The measurement scheme of the probe characteristics of the emission plasma

Using the automated measurement system, spatial characteristics of the emission plasma were obtained under different conditions of its generation (type of gas, operating pressure, discharge current amplitude, resistance in the hollow anode circuit of a plasma emitter).

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GAS HEATING DYNAMICS IN A PULSE MICROWAVE DISCHARGE IN AIR*

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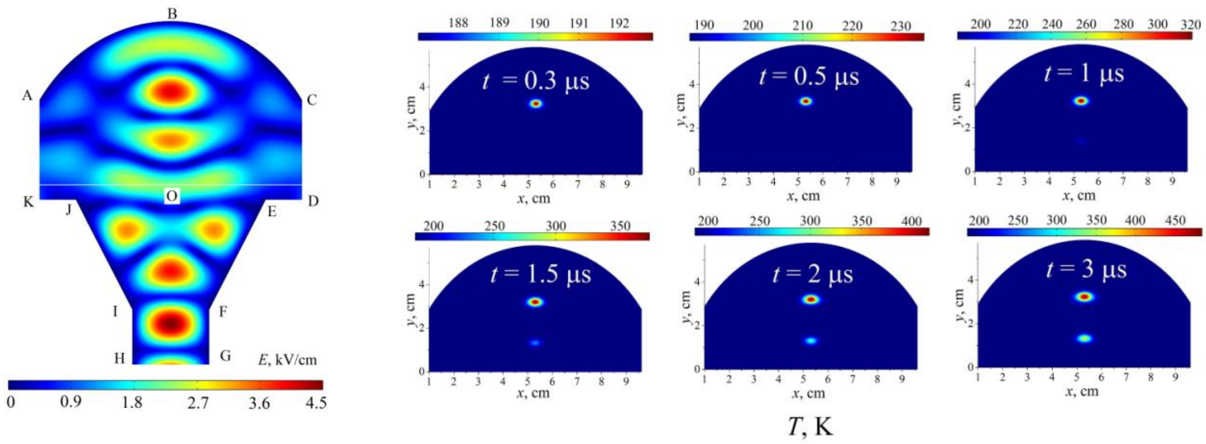
Progress in microwave electronics opened the possibility of initiation of an electrodeless microwave discharge in free space in a wide range of external conditions. Initiation of a microwave discharge is a convenient method of supplying energy to super- and hypersonic gas-dynamic flows for controlling their characteristics.

In particular, studies aimed at investigation of the influence of a microwave discharge on shock wave structures and streamlining of bodies by a supersonic flow, as well as at finding optimal parameters of the discharge for achieving the strongest aerodynamic effect, were conducted in [1]. A special focusing system representing a cylindrical paraboloid that allows localizing the microwave discharge in its focus was proposed in [1]. The parameters of such a focusing system were used in the present study to perform numerical simulations.



a b

Fig.1. The spatial distribution of a) the intensity of the electric field generated by the microwave wave, b) the gas temperature at different points in time.

The present work is aimed at computer simulation [2] of the spatiotemporal dynamics of a focused pulsed microwave discharge in air under the conditions of the experiments carried out in [1].

The numerical experiments have demonstrated that two microwave discharges (plasmoids) appear in the focusing system proposed in [5-7]. Information on the dynamics of the main plasma parameters in these discharges (in particular, on the distributions of the electron density and electric field strength) was obtained. The dynamics of neutral gas heating was analyzed. It is demonstrated that the maximum gas heating is achieved in the microwave discharge excited in the focus of the system. The maximum temperature of 474 K is reached in 3 μs for a deposited power of 200 kW, which agrees with the experimental data obtained in [2].

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KINETICS OF ELECTRONS AND IONS DURING THE FORMATION OF LOW-PRESSURE GAS DISCHARGE*

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Low pressure gas discharge at high voltage is often used in lab and industry devices. A feature of this discharge is that the electron mean free path is higher or comparable to the interelectrode gap. This leads to the fact that only a small fraction of the electrons is able to ionize the gas, ions slowly accumulate in the gap and distort the spatial distribution of the electric potential. At a more simplified level, this process is described in earlier papers [1, 2].

The spatial and temporal structure, as well as the energy spectra of the plasma components are one of the most informative characteristics of the gas discharge. To date, only theoretical modeling is able to provide such information with sufficient time resolution.

Our paper presents a theoretical one-dimensional model of a low-pressure gas discharge. We considered the process of plasma propagation from a cathode spot with a high density of injection current into a gap with a spherical geometry filled with nitrogen. We were not interested in the nature and processes occurring in the cathode spot, therefore the injection current is constant. The plasma included singly charged ions and electrons, the both plasma components were described by the Boltzmann kinetic equations. The right side of the equations took into account ionization and elastic collisions with gas atoms. The system of equations was complemented with the Poisson equation.

For the first time, the results of a fully kinetic modeling of the initial stage of a low-pressure discharge after its initiation by a cathode spot are presented. The complete dynamics of the electric field and the distribution functions of electrons and ions in the gap are traced in time. The figure shows an example of calculating the evolution of the potential distribution during the breakdown of a spherical diode (cathode radius 1 mm, anode radius 51 mm) filled with nitrogen at a pressure of 10 Pa and an anode voltage of 10 kV.

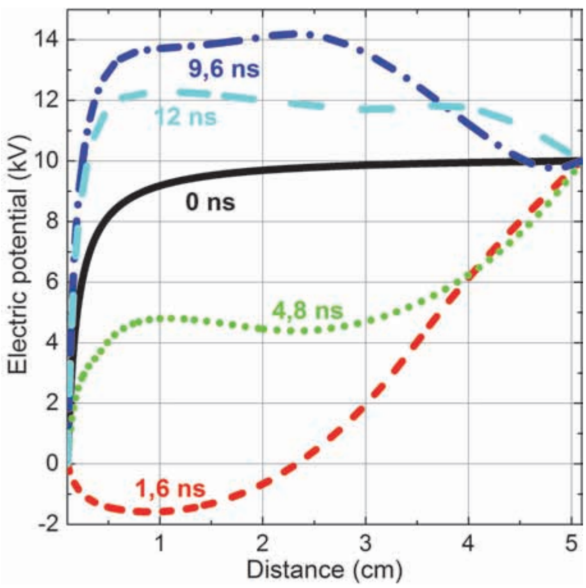

Fig. 1. Spatial distribution of electric potential in the gap at different points in time. Cathode plasma density is fixed at $2\cdot10^{11}$ cm^{-3}.

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DISCHARGE FEATURES IN CROSSED ELECTRIC AND MAGNETIC FIELDS *

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The conducted studies expanded the set of phenomena and features that characterize the anomalous self-sustained Hall $E\times B$ discharge in a plasma accelerator with an anode layer (TAL). Some of the results add to the known data while some of the conclusions may constitute the new findings.

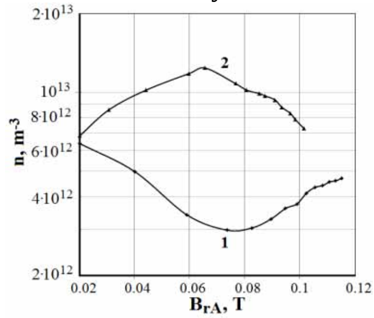

Fig. 1. Dependence of ion density at the TAL output on the magnetic field induction at the anode: curve 1 – $B_{zA}/B_{rA} \le 5\%$; 2 – $10\% \le B_{zA}/B_{rA} \le 15\%$; neon; $U_d = 1100$ V; $P = 9{\cdot}10^{-5}$ Torr.

In the case of $10\% \le B_{zA}/B_{rA} \le 15\%$ (B_{zA}, B_{rA} – longitudinal and radial components of the magnetic field induction, a so-called "optimal *B*" effect was observed as the nature of the change in *n* upon the increase in magnetic field induction was fundamentally different: a certain value of *B* led to the maximum in the ion density (Fig. 1, curve 2) unlike the minimum known from the early works (Fig. 1, curve 1).

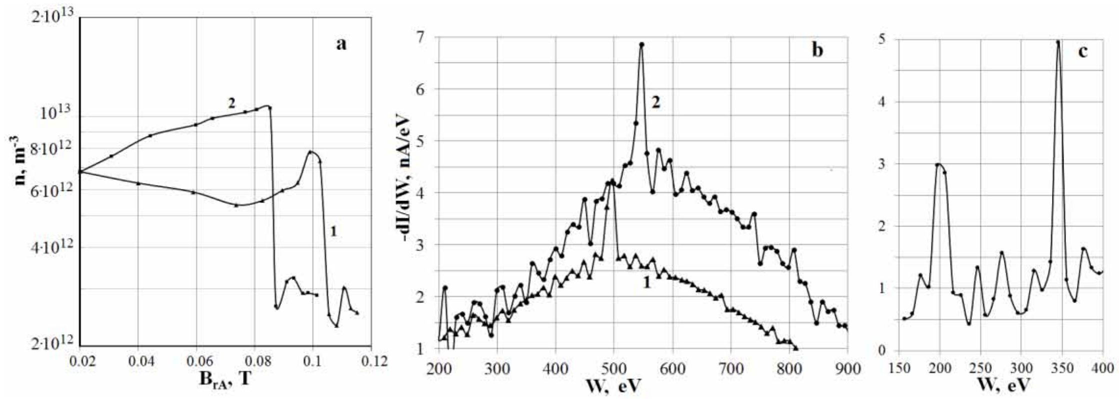

Fig. 2. a – Dependence of ion density at the TAL output on the induction of the magnetic field at the anode: curve 1 – $B_{zA}/B_{rA} \le 5\%$; 2 – $10\% \le B_{zA}/B_{rA} \le 15\%$; argon. Energy spectra of ions at the TAL output: $U_d = 1100$ V; $P = 9{\cdot}10^{-5}$ Torr; b – neon, curve 1 – $B_{rA} \approx 0.099$ T, 2 – $B_{rA} \approx 0.085$ T; c – argon, $B_{rA} \approx 0.099$ T.

Parameters of the discharge in the process of growth of the magnetic field may change dramatically (Fig. 2a, curves 1, 2), emphasizing the threshold nature of the processes in TAL plasma.

Upon refusal from the approximation of the RFA delay curves, it is possible to see the fine energy structure of the spectra which is spatially limited, the estimate provides an axial size of the order of tenths of mm, stationary regions of significant E_z – one or two (Fig. 2b, 2c) isomagnetic potential jumps (from $\sim$ 30% to $\sim$ 80% of the total current) which induce ion density jumps. In the energy spectra, this is manifested as peaks of the distribution function within narrow energy ranges. The isomagnetic jumps "move" with the spectrum up or down along the energy subsequent to the changes in magnetic induction.

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SPECIES KINETICS IN Ar-S_2 PLASMA OF THE PULSED PERIODIC DISCHARGE

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The problem of creating effective light sources is one of the old, but not lost its relevance. All known light sources, such as incandescent, fluorescent, halogen, mercury, sodium, metal halide, xenon, sulfuric lamps and LED lamps have, along with advantages, significant disadvantages [1]. One of the directions for improving lighting systems is plasma lamps based on sulfur vapour radiation. Discharges in mixtures of noble gases with sulfur vapors allow obtaining spectrum of radiation, close to solar; such spectrum is caused by radiation of S_2 dimers, which bands of the $B\,^3\Sigma \rightarrow X\,^3\Sigma$ system are approximately on equal distances from each other and merge in a continuous spectrum in the wavelength range of 280-600 nm [2].

Here kinetics of charged and neutral species in Ar-S2 plasma of the pulsed periodic discharge is studied. Species densities during voltage pulses were calculated using a global model of the pulsed-periodic discharge in sulfur vapours – argon mixtures. The kinetic (0-D) model is based on solution of the kinetic equations for plasma species and an equation of the electron energy balance. The kinetic scheme includes 33 reactions for 14 species: Ar, S_2, S, Ar_r*, Ar_m, Ar**, $S_2^*(B^3\Sigma_u^-)$, S*, S_2^+, S^+, Ar^+, S_2^-, S^- and electrons. The simulations were performed for experimental conditions of a longitudinal pulsed periodic discharge in mixtures of argon and sulfur vapors that was studied in Institute of Electron Physics (Uzhhorod) [3].

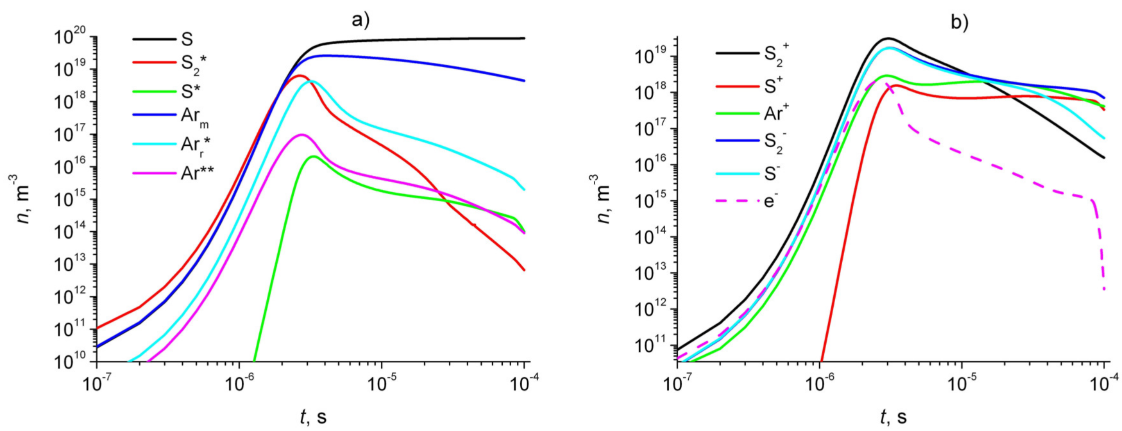

Fig. 1. Dependence of species densities on time during the voltage pulse: a) neutral species, b) charged species; U_{max}=7kV, τ_P~10μs, P_{Ar}=40 Torr, 2% S_2 in Ar-S_2 vapour mixture.

Figure 1 shows changing species densities in 0.98Ar-0.02S_2 mixture during the voltage pulse. One can see during whole time the principle charged species are positive and negative ions. All excited species are formed at time intervals when electron energy high enough ~ 3-5eV. In the figure the first jump in excited and charged species densities is caused by high field at pulse front. When pulse voltage falls, electrons and emitting species densities fast decrease.

It is shown, that a breaking field E^*/N, at which a transition from electronegative to electropositive plasma takes place, increases with sulfur vapour fraction in Ar-S_2 mixture. The discharge with electropositive plasma is non-stable and can exist during short time in pulsed discharge. Under $E/N<E^*/N$, when plasma is a bit electronegative, S_2^+ ions are primary positive ions in Ar-S_2 plasma and under $E/N<<E^*/N$, when plasma becomes very electronegative, S^+ and Ar^+ are primary positive ions. In both cases the negative ions S_2^- and S^- are in commensurable amounts in the plasma. The strong radiation of S_2($B\,^3\Sigma \rightarrow X\,^3\Sigma$ - transition) inheres for electronegative mode of the discharge.

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EMISSION AND LEVEL POPULATION IN NOBLE GASES AND THEIR BINARY MIXTURES IONIZED BY ION BEAM*

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The main processes in the plasma created by electron or ion beams are similar to processes in a gas-discharge recombining plasma. Interest in the study of spectral-luminescent properties of low-temperature plasma excited by ionizing radiation stems to the fact that such plasma is an active medium of gas lasers with nuclear or beam pumping, scintillation detectors, as well as in spontaneous emission sources.

Research was held at the DC-60 heavy ion accelerator, $^{40}Ar^{+7}$ ions accelerated to 70 MeV were used in present experiments. Frequency of ion rotation is up to 16 MHz, duration of the beam is 18 ns. The accelerated ion beam passes from evacuated transportation channel through 3 mm hole in the flange to irradiation chamber. The emerging light radiation passes through quartz window and condenser lens and focused on optical fiber. The beam falls on a compact spectrometer (QE65Pro or USB-2000+, Ocean Optics) through the fiber.

The continuous spectra of pure gases were presented by the “third continuum” of Ar, Kr and Xe, the weak band was observed in neon in the range of 200-370 nm. Strong bands of transitions of $ArXe^+$ (with maxima at 329 and 506 nm), $KrXe^+$(491 nm), $ArKr^+$(642 nm) were observed in the binary mixtures of noble gases, having said that transitions from lower levels of heteronuclear ionic molecules are absent in Kr-Xe and Ar-Kr. Week bands with maxima at 346, 349 and 545 nm, associated with transitions from $Ar(^2P_{3/2})^+Xe$, are present in the Ar-Xe mixture.

In helium were observed bands of first negative system of nitrogen, 706.5 and 667.8 nm lines comparable with them in intensity and weaker 501.6 nm, 587.5 nm, 706.5 nm, 728.1 nm lines. In other noble gases prevails lines of 2p-1s transitions (Paschen notations).

Distribution of emission intensities by 2p-levels of atoms noticeably differs from flow distribution of molecular ions dissociative recombination by levels, given in [1]. The significant part of the flow of Ar_2^+ dissociative recombination refers to the $2p_9$ level in argon, while about half of the radiation refers to $2p_2$ level (table 1). The half of radiation occurs from $2p_5$ level in xenon, there is only 4% of the flow of Xe_2^+ ion recombination at this level. 19% of Kr_2^+ recombination flow goes to $2p_2$ level in krypton, less than 5% of 2p-level photons is emitted from this level. Apparently, population of atomic 2p-levels of noble gases happens in cascade transitions from d-levels [2, 3], and the dissociative recombination of molecular ions with electrons is not the major process in population of 2p atomic levels of noble gases.

Effect of additives of the electronegative gases (O_2, CCl_4) on luminescence spectra of argon and xenon was investigated.

Table 1. Emission intensity distribution (in percentage) on the 2p levels of Ar in argon and Kr in krypton

Level		$2p_1$	$2p_2$	$2p_3$	$2p_4$	$2p_5$	$2p_6$	$2p_7$	$2p_8$	$2p_9$	$2p_{10}$
Ar, 80 kPa		3.1	49.2	2.8	3.2	0	17.0	2.5	5.3	2.7	14.2
Kr, kPa	27	0.8	5.8	2.8	2.7	0	45.2	12.1	10.6	16.1	3.9
	53	1.1	5.3	2.8	2.5	0	45.7	11.8	9.7	17.3	3.8
	80	0.7	5.3	3.0	2.6	0	45.2	12.6	9.3	17.1	4.2

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PROBE DIAGNOSTICS OF THE PLASMA PLUME CREATED BY A MAGNETIC NOZZLE OF AN INDUCTIVELY COUPLED PLASMA SOURCE*

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In the last decades, a significant interest has been focused on the electrodeless methods of the plasma accelerating [1-3]. One of these methods is application of a magnetic nozzle.

Plasma flowing through magnetic nozzles has been observed in many natural systems and is used in a variety of terrestrial applications ranging from electric propulsion to plasma processing [4].

A magnetic nozzle, consisting of an applied convergent-divergent axysimmetric magnetic field, constitutes the main acceleration stage of several advanced plasma propulsion concepts such as the Helicon Plasma Thruster [5-7], the applied-field magnetoplasmadynamic thruster [8,9], the Variable Specific Impulse Magnetoplasma Rocket (VASIMR) [10] and ,marginally, in the Diverging Cusped Field Thruster [11] and coaxial magneto-plasma accelerator [12].

Similar to de Laval nozzles that convert random thermal motion into directed flow, magnetic nozzles are used to redirect the motion and momentum of the plasma flowing through the nozzle. To this end, a magnetic nozzle can be used to improve thrust efficiency and provide a means of controlling the plume geometry and plasma energy distribution functions.

This paper presents the experimental and computational studies results on the plasma characteristics in the plume created by the magnetic nozzle of the inductively coupled plasma source. The studies were carried out under different parameters (including the types of feed gases, RF-power, types of inductors, etc.).

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A LIMIT VALUE OF THE VOLUME DISCHARGE IGNITION FREQUENCY IN DENSE GASES

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1. Introduction

At the present time some laser technologies need the in the laser pulses, which generated at pulse repetition rates up to 10÷20 kHz with energy per pulse 10÷50 mJ and pulse duration 10÷50 nanoseconds. Modern types of TEA–CO_2 lasers work at the pulse repetition rates less than 1 kHz. Maximum value pulse repetition rate depends from many factors. They are connected with the volume processes in gas mixture in high speed gas flow between of electrodes and on the electrode surfaces. All of them influence on the volume discharge transition into the local one. The nature of this transitions are described in [1÷3]. Such local discharges can not use for pumping of TEA–CO_2 lasers.

The main goal of this work was determination of the limit value of the volume discharge ignition frequency in dense gases especially in CO_2–laser mixtures at atmospheric and superatmospheric pressures.

2. Results of theoretical and experimental investigations

The maximum pulse repetition frequency of volume discharge ignition is limited by the time of smoothing of inhomogeneities of gas density, chemical composition and temperature in the discharge gap and also thermal inhomogeneities on the electrode surfaces. The appearance of these inhomogeneities is conditioned by inhomogeneities of the volume discharge current density or by the forming of local discharges. In the case of accumulating thermal inhomogeneities in gas or at the electrode surfaces volume discharge transforms to the local one. The inhomogeneities in the discharge gap volume may be considerable decreased or removed during several milliseconds at pause between the pulses by high speed gas flow, but it is necessary considerably more time for the smoothing of local thermal inhomogeneities on the electrode surfaces. On the base of instationary heat–conduction equation and interrelations between geometrical dimensions of cross–section of spark channel with time was obtained the next expression for maximum value of the volume discharge ignition frequency in dense gases:

$$F_{MAX} = B_*[a/L_*C_*U], \qquad (1)$$

where – B –constant, which depends from chemical composition and total pressure of gas mixture; a – coefficient of electrode material temperature conductivity; L, C and U – inductance of the discharge circuit, capacity of accumulating condenser and charge voltage.

The decrease of the local discharge current duration and consequently of the thermal inhomogeneities smoothing time can be attained by decrease of the capacity of accumulating condenser of the pulse pumping generator. The realization of this condition when the preservation of high density of the pumping energy is connected with the division of the discharge gap in several parts and simultaneous excitation of volume discharge in these parts by the separate pulse generators. In this case the forming of the local discharge (it is always inevitable!) in separate part did not cause full development of the volume discharge into local one because of negligible dimensions of thermal inhomogeneities on the electrode surface and consequently the fast cooling of it. In this work the electrode structure from three sections with 15 cm common length was used for the increase pulse repetition rate of volume discharge and the for more stability operation.

The cross–section of discharge gap was $1.2_*0.6$ cm^2. The volume discharge was excited by three identical pulse transformers with simultaneous switching of thyratrons and careful agreement of which transformer with discharge section. The 200 mJ$_*$cm^{-3} energy density stable volume discharge was realized with pulse repetition rate up to 5 kHz for gas mixture CO_2:N_2:He=1:1:8. The maximum pulse repetition rate for electrodes without division in section was less 2 kHz for this conditions.

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MEASURING THE VELOCITY OF STREAMERS FORMED IN AN INHOMOGENEOUS ELECTRIC FIELD*

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Diffuse discharges in gaps with an inhomogeneous electric field distribution are the simplest and most common method to produce dense non-equilibrium low-temperature atmospheric-pressure plasma in atomic and molecular gases. There are many scientific groups studying the discharge development in the inhomogeneous electric fields [1–5]. However, the dynamics of the streamer development at different values of the breakdown delay time and voltage pulse polarities is not fully studied.

The formation of positive and negative streamers in a point-to-plane gap filled with atmospheric-pressure air has been experimentally studied using a Hamamatsu C10910-05 streak camera and a HSFC-PRO four-channel ICCD camera. Nanosecond voltage pulses were applied across the gap. Waveforms of voltage and discharge current pulses were also recorded. In addition, a dynamic displacement current induced by a streamer when it propagates in the gap was measured with a sensor placed behind a grounded grid electrode. The formation of a large diameter streamer was observed with the ICCD camera at various amplitudes of nanosecond voltage pulses. The streamer originated in the vicinity of the pointed electrode. It was like a ball at the initial stage due to the distribution of the electric field in the gap. The initial streamer velocity was high, but it quickly decreased with an increase in its diameter. The minimum streamer velocity corresponded to the maximum diameter. The streamer velocity increased when the streamer approached the opposite electrode.

It was found that when the streamer appears in the vicinity of the pointed electrode, a current through the gap increases rapidly. This current is induced by the streamer due to the redistribution of the electric field. For this reason, we call it the dynamic displacement current. The value of the dynamic displacement current correlated with the instantaneously streamer velocity. It was shown that the dynamics of the electric field strength near the grounded grid electrode can be determined by integrating the dynamic displacement current. At negative polarity, it is possible to investigate simultaneously the generation of runaway electrons and the formation of the negative streamer. In particular, it was found that runaway electrons are generated in the time interval covering the beginning of the electron emission from the pointed cathode and the crossing by the streamer of approximately one third of the distance to the grounded anode.

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DISCHARGE DEVELOPMENT IN THE SALINE SOLUTION AT ABOVE THRESHOLD VOLTAGES

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At present, discharges in electrolytes, i.e. the flow of electric current under the action of the applied voltage in conductive liquids, are widely used in medicine, biology, echolocation, etc. [1, 2].

One of the features of the current flow in electrolytes is that the gas cavities occur in the gap already at low values of the applied voltage. In the case when this voltage reaches a certain threshold value, which we define as a critical voltage, a discharge ignites in the cavities and plasma appears [3, 4]. In [4] the results of studies of the processes of formation and disappearing of gas cavities, as well as the occurrence of plasma in them under conditions where the voltage applied to the interval is less than or equal to the threshold value are presented. This work is devoted to these studies for voltage exceeding the threshold value.

The paper deals with the processes occurring in a three percent NaCl solution in water for the pin-plane electrode geometry. The interelectrode gap is 1 cm. The pulse duration applied to the interval lies in the micro and millisecond time interval, and the voltage amplitude is 800-3500 V. The maximum value of the current is several kA. A set of data on the process of formation, development and degradation of gas cavities is presented. The physical mechanism of evolution of these cavities is analyzed. Data on the formation of gas-discharge plasma in cavities such as CCD camera photos, photoelectronic measurements of the time interval luminescence, spectral measurements are presented. The forms of discharge combustion is discussed. It is concluded that the formation of gas cavities and the occurrence of plasma in them has a significant impact on the nature of the flow of current in the gap.

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MECHANISM OF HIGH EFFECTIVE GENERATION OF ELECTRON BEAMS IN HIGH-VOLTAGE DISCHARGE IN HELIUM AND ITS MIXTURES WITH NITROGEN AND OXYGEN.*

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High-voltage discharges in helium and its mixtures with oxygen for a long time are used to generate electron beams (EB) in medium-pressure gases. Nevertheless, the question of the most important properties of such discharges, in particular, the current-voltage characteristics, the efficiency of the generation of electron beams, the mechanisms of electron emission from cold cathodes, and the effect of helium purity on these parameters are debated up to this day. In this report, studies of the current – voltage characteristics and the efficiency of generation of EB in discharges in helium and its mixtures with nitrogen and oxygen have been conducted.

Studies were conducted in carefully outgassed cells with helium of purity no worse than 99.999%. It turned out that under these conditions, the I – V characteristic with a pressure of more than 10 Torr, as the voltage rises, realizes an exponential law of the I – V characteristic, then slows down its growth until a falling portion is obtained, and at a voltage higher than 1.5 kV, the rapidly increasing characteristic with current density $I = U^y$ with the value of y = 5-15. The appearance of the current – voltage characteristics in the initial region is explained by the exponential dependence of the Townsend multiplication factor α on the voltage U. As U increases, the growth of α slows down, passes a maximum, and then α rapidly decreases. The emission of electrons in the initial segment is carried out under the action of ions, metastable atoms and photons and weakly depends on U. At U> 500-600V, electron runaway from the cathode fall region begins to play a significant role, which, together with the fall of α, leads to a fall in the IVC. At U> 1.5 kV, an electron beam is formed, the photo-illumination of the cathode by resonant VUV radiation is amplified, and the current – voltage characteristic again acquires a rapidly increasing character. At U> 3.5kV, due to the predominance of photoemission, the efficiency of generation of EBs reaches 85%.

The introduction of oxygen or nitrogen in small quantities (less than 2%) dramatically increases the discharge current --- up to two orders of magnitude and, at a helium pressure of less than 4 Torr, increases the efficiency of generation of EF. This increase is associated with a large value of <γ> - kinetic emission under the action of fast molecular particles. In turn, the high value of <γ> is due to the interaction of fast heavy particles with the surface layers of cathodes doped with these particles. The results obtained make it possible to interpret from the unified point of view the entire diversity of the I – V characteristics in the discharges both in pure helium and in mixtures with molecular gases and to determine the conditions for achieving highly efficient generation of EB.

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UNSTABLE PLASMA-SURFACE INTERACTION AND AUTO-OSCILLATING DISCHARGE REGIMES

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Microwave and RF discharges along with high frequency methods of charged particles acceleration and plasma heating are widely used in technology and fundamental researches. Self generation of electromagnetic oscillations in the gas discharge circuit with a DC power supplier due to intrinsic instabilities provides auxiliary possibilities to enhance the ionization, plasma heating and ion acceleration. Very powerful auto-oscillations can be generated due to unstable plasma-surface charge exchange when a non-equilibrium plasma interacts with negatively biased surfaces exhibiting enhanced secondary emission which is especially large in presence of thin (5-10 nm) dielectric layers [1-5]. Due to a very fast dinatrone feedback the frequency range of auto-oscillations can spread up to GHz range.

The main emphasis of this work is maid on studding of the discharge conditions when emissive layers can be formed and exist on the electrode surface. The case of thin self-oxide dielectric layers uniformly covering the electrode made of aluminum, beryllium, tungsten and tantalum is most interesting for practice. The drastic change of the contact current voltage characteristic from the monotonous probe type with a very low ion saturation current to the N-type in presence of emissive layers is illustrated by fig. 1a. The emission current exceeds the electron saturation current by an order of magnitude due to a field tunneling of electrons from the metal to the plasma through the dielectric layer. The resulting strong amplifying effect leads to the autogeneration of electromagnetic oscillations in discharge circuit accompanying with increasing of plasma density and power consumption from a DC supply. The example of a phase trajectory for alternating voltage and current is presented in the fig. 1b. It demonstrates the evolution of auto-oscillations from a low amplitude mode to a low current-high voltage mode and then to a high current mode with enhanced plasma generation.

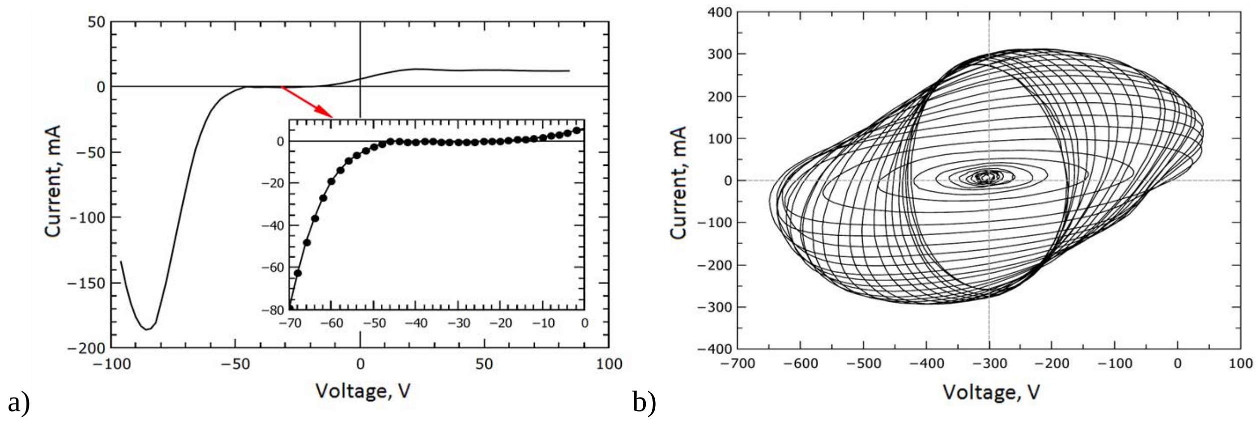

Fig. 1. N-type current-voltage characteristic of the aluminum electrode (a) and a phase trajectory for alternating voltage and current (b) in auto-oscillating discharge regime.

The mode with high voltage pulses in relaxation regime with a large external inductance can provide amplitudes of the order of 50kV and can be used for ion implantation. The high current mode in harmonic regime of high frequency autogeneration is convenient for production of intensive plasma flows.

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REGIMES OF THE DICHARGE SUSTAINMENT IN THE TRIGGER UNIT OF SEALED-OFF COLD-CATHODE THYRANRON[*]

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Currently, high-current switching devices based on low-pressure hollow-cathode pulsed discharge (so-called pseudospark switches) are widely used [1-5]. The design and principle of operation of these switches are close to those of a classical hot-cathode hydrogen thyratrons. However, these devices do not have a hot cathode. Therefore, pseudospark switches are often called cold-cathode thyratrons or thyratrons with a grounded grid [6–8].

As in the case of classical thyratrons, a range of operating pressures of the switch corresponds to the left branch of Paschen's curve. Under these conditions the electron free path for ionization is much in excess of the electrode separation. For both self-breakdown of the main gap of the thyratron and for external discharge triggering a considerable pre-breakdown electron current is required [6-8]. For the case of external triggering, this current is provided due to a special trigger unit that is placed in the main cathode cavity. Various types of the trigger units are presented, for example, in [2, 9, 10].

By now, the sealed-off metal-ceramic devices have been developed and manufactured. The first devices have been described in the review [9]. Currently, these devices are commercially produced in the Pulsed Technology Ltd. (Ryazan, Russia, http://www.pulsetech.ru). Different triggering methods have been employed in these devices. In particular, in the thyratrons of the TPI type, the trigger unit is based on an auxiliary glow discharge [2, 10].

The operation conditions of the auxiliary glow discharge substantially affect the thyratron characteristics as a whole [10-13]. In particular, this concerns the breakdown voltage, the time delay of breakdown in the main discharge gap with respect to the triggering pulse, and the pulse repetition rate. Therefore, considerable attention is paid to the choice of the operating modes of the auxiliary discharge and the design of the electrode system of the device.

In this report, we present results of studying the operation of the auxiliary glow discharge in sealed-off thyratrons of the TPI series. The current-voltage characteristics were obtained and analyzed. A model of the current sustainment in a hollow-cathode discharge was used for explanation of the discharge regimes. Transition from hindered glow discharge to conventional hollow-cathode glow discharge is investigated.

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FEATURES OF THE SUSTAINMENT OF LOW-PRESSURE GLOW DISCHARGE WITH THE HOLLOW-CATHODE AND HOLLOW-ANODE*

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Hollow-cathode low-pressure glow-type discharges are widely used for different applications [1-5]. In particular, such discharges are used for generation of charged particle beams, for surface modification, for generation of extreme ultraviolet radiation, for generation of large volume plasmas and so on. One of the applications is in the high-current switching devices (so-called pseudospark switches). The design and principle of operation of these switches are close to those of a classical hot-cathode hydrogen thyratrons. However, these devices do not have a hot cathode. Therefore, pseudospark switches are often called cold-cathode thyratrons or thyratrons with a grounded grid [5–9].

As for the classical thyratrons, a range of operating pressures of the switch corresponds to the left branch of Paschen's curve. Under these conditions the electron free path for ionization is much in excess of the electrode separation. For both self-breakdown of the main gap of the thyratron and for external discharge triggering a considerable pre-breakdown electron current is required [3, 8, 9]. For the case of external triggering, this current is provided due to a special trigger unit that is placed in the main cathode cavity.

Various types of the trigger units are used in the switches [5, 8, 10-12]. One type of the trigger devices is based on an auxiliary low-current hollow-cathode glow discharge. In the sealed-off thyratrons, that are produced commercially, trigger unit consist of hollow cathode and ring anode. For reduction of auxiliary discharge ignition and burning voltages, a special high emissivity tablet is used. It represents a cylinder that is fabricated from powder materials by means of hot-pressing and sinter technology and is placed at the bottom of the cavity of auxiliary discharge. Unfortunately, the tablet composition effects to the parameters of the auxiliary discharge. In turn, the conditions of the auxiliary discharge burning determine the rating characteristics of the switch itself [7, 10, 11].

In this report, the data on the regimes of the auxiliary glow discharge with a hollow cathode and hollow anode are presented. As a distinct from the sealed-off thyratrons with the ring anode of a trigger unit, current investigations were carried out with the demountable quartz chamber with modernized trigger unit without high-emissivity tablet. The electrodes of the modernized trigger unit represent two cups, faced to each other by open sides. During the experiments, current-voltage characteristics and the images of the discharge for the different electrodes dimensions were obtained. Two discharge regimes were observed: the so-called hindered glow discharge and the conventional glow discharge. A model of the current sustainment of a hollow-cathode discharge [6, 12] was used for estimations of discharge parameters. The results of estimations agree well with the experimental data.

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GENERATION OF UNIFORM BEAM-PLASMA FORMATIONS IN LARGE VACUUM VOLUMES [1]

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Electron-ion-plasma methods of surface hardening and improvement of consumer properties of products are considered advanced due to high environmental friendliness and wide opportunities [1]. Surface treatment of materials and products in a gas or gas-metal plasma at low pressure (≈ 1 Pa) has a number of significant advantages, including low content of residual elements (e.g. oxygen), the ability to independently adjust of all main operating parameters - ion energy, ion current density, working pressure, substrate temperature. Adjusting the operating parameters in a wide range and the synthesis of the plasma medium with the required saturability allow to form layers on the surface with the required structure and phase composition, to find relatively low-temperature modes of material processing. Promising for practical applications is the beam-plasma formations, which allows realize an ionic and electronic influence on material surface.

A glow discharge with a hollow cathode [2] and its non-self-sustained form of combustion [3-4] with external injection of electrons is promising for the generation of such beam-plasma mediums in large vacuum volumes. The plasma synthesized in hollow cathode glow discharge with external electron injection by the method of its generation can be attributed to beam-plasma formations. Beam-plasma formation (BPF) is a plasma medium, for generation of which, firstly, it is necessary to have an electrode system providing discharge self-maintenance in a certain range of operating parameters or discharge burning with some degree of lack of independence and determining the degree of non-uniformity of plasma density. Secondly, it is necessary to inject a beam of charged particles, for example electrons, into the discharge system, which is significantly changes the characteristics of the discharge and plasma parameters and its composition and moreover, the beam initiates additional plasma interactions near the substrate and makes physical and chemical impact on the substrate surface. The objects treated in the plasma medium generated in non-self-sustained hollow cathode glow discharge are placed at cathode potential or a negative bias is applied to them from a separate power supply.

The paper considers a generation of beam-plasma formation in a plasma source based on a low-pressure (≈1 Pa) high-current (up to 450 A) non-self-sustained glow discharge with a hollow cathode of volume ≈0.2 m^3. Research data are presented on the ignition stability of the discharge, on its main parameters, and on the radial and azimuthal plasma inhomogeneity varying with pressure, discharge voltage and current, and anode-to-cathode area ratio at a plasma density of $\approx 10^{18}$ m^{-3} and ionization degree of ≈1 %. The beam plasma formations synthesized in such electrode system of non-self-sustained glow discharge with a hollow cathode are interesting both from a scientific and technical point of view.

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MONTE-CARLO SIMULATION OF THE IONIZATION PROCESSES FOR DISCHARGES IN THE LEFT BRANCH OF PASCHEN'S CURVE*

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The paper deals with the development of the simulation methods as applied to the low-pressure discharges in which the reduced electric field E/p is extremely high and there exists a problem for the correct description of the ionization processes in the classical electron avalanches. In some conditions, the electron free path for ionization can be comparable with the interelectrode gap so that the notion of electron avalanche is not applicable at all. Typical examples are the discharges in the so-called pseudospark switch and in the plasma sources of electron and ion beams [1].

It seems that one of the computer codes that would be applicable for discharge modeling in such conditions is the PIC/MC xoopic [2, 3]. This code offers a possibility to compute the spatial and temporal distribution of electric field self-consistently with the temporal changing of the excess space charge of electrons and ions. The block taking account the ionization processes is based on the Monte-Carlo method. One of the advantage is that the computer program has the open code and we are able to modify the primary data on the cross sections and the calculation algorithm in accordance with the particular problem, which is solved [4].

Here we use the above code for calculation of the impact ionization coefficient α, the electron drift velocity and the electron diffusion coefficient D in the electron avalanches in nitrogen. The range of calculations covers the ratio $E/p \leq 1000$ V/(cm·Torr). An example of calculation of the coefficient α is presented below.

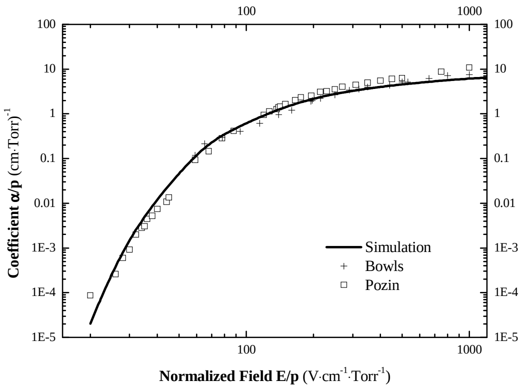

Fig. 1. Coefficient α from simulation (nitrogen, 20 Torr) and experiments [5].

Formally speaking, even for extremely high reduced electric fields we have a reasonable agreement with the experimental data. However, the interpretation of the results in terms of the electron avalanches for $E/p \geq 1000$ V/cm leads to incredibly high electron diffusion coefficient and electron temperature at a level of $kT_e \approx 30$ eV, i.e. larger than the ionization potential [4]. The data on spatial distribution of electrons in the gap, obtained with a usage of Monte-Carlo simulation, show that for a moderate E/p values the electron cloud is located inside the gap and has a spherical shape. As for the high E/p, we can hardly speak of the electron avalanche in its generally accepted representation. Here the electron cloud does not have space and time to take shape in the gap. The physical reasons for the described effect and the features of ionization at high E/p are discussed in detail in the present paper.

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PLASMA TRANSFER AS A WHOLE*

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Sunce the first systematic studies of the beginning of the last century, the concept of local ionization-recombination equilibrium is dominant in describing the balance of charged particles of gas discharge plasma. Calculations of the characteristics of gas discharge plasma are based on models of local equilibrium [1], whereas fields observed experimentally at high pressures that are low for ionization are explained by the multi-stage processes of particle production in the bulk [1, 2]. However, electron and ion fluxes coming from the near-electrode layers at moderate and, especially, atmospheric pressures, are sufficient to ensure the balance of particles in the discharge plasma without ionization in the bulk [3]. Moreover, if we consider the motion of charged particles of the positive column in detail, it is easy to see that even in a classical discharge at low pressures (0.01-1 *Torr*) particles with different signs of charges recombining on the walls in the selected tube cross-section (S) come from different parts of the discharge (Fig. 1). The positive ions (i) moving in the cross-section under the action of ambipolar diffusion simultaneously have a velocity component directed from the anode. The electrons (e) coming to the tube walls together with these ions arrive from the cathode side, and the overwhelming number of electrons generated in the cathode layer pass through the entire tube volume to the anode practically without losses. Only at low pressures (of the order of 0.01 *Torr* and less) the areas of generation and death of particles can be comparable with each other, although this is also quite questionable, since the mean free path becomes comparable to the radius of the tube and the physical meaning of the concept of local balance is lost.

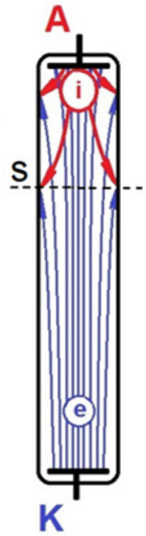

Fig. 1 Diagram of the motion of charged particles in a tube.

In our papers we show [4-7] that at moderate and atmospheric pressures not only fluxes from the electrode side determine the longitudinal structure of the discharge, but also the plasma transfer as a whole [8], together with the thermal potential nT and the plasma electric field energy potential $\rho\varphi$ determine the transverse structure of the discharge. Moreover, bulk ionization and recombination losses are not considered. It is shown that the atmospheric pressure stationary discharge [9, 10] exists only in a well-heated gas when molecular ions are absent and the losses are determined by ambipolar diffusion [11].

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PREBREAKDOWN CURRENTS IN THE TWO-SECTIONED COLD-CATHODE THYRATRON AND THEIR ROLE IN MECHANISM OF STATIC BREAKDOWN*

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The data on measuring the prebreakdown currents and the static breakdown voltages as applied two-sectioned sealed-off thyratron TPI1-10k/50 are presented [1]. Schematic of the thyratron and illustration of the method of measurement are shown in Fig. 1.

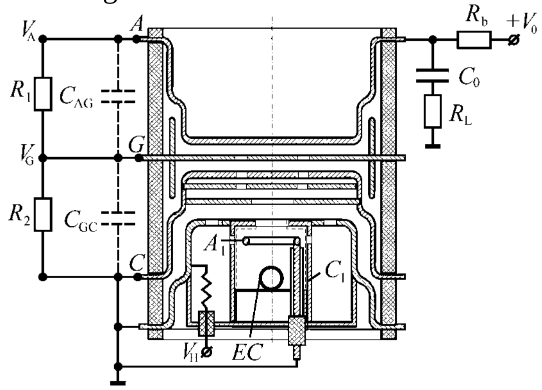

Fig. 1. Schematic of experiment. *A* – main anode, *C* – main cathode, *G* – gradient electrode, V_H – voltage at the heater of hydrogen reservoir. C_0 = 10 nF, R_b = 7.5 MΩ, capacitance of the upper section C_1 = 40 pF, capacitance of the lower section C_2 = 29 pF.

In the experiments, we measured the prebreakdown currents, the static breakdown voltages in the thyratron as a whole V_{br} and the breakdown voltages and prebreakdown currents in the separate sections of the device. The summary of the data are shown in the table below, where V_{br1} is the breakdown voltage of the upper section, V_{br2} is the breakdown voltage of the lower section. V_{Acr} is a critical anode voltage with which the static breakdown voltage at the lower section would be achieved if the voltage over the sections were distributed in accordance with the capacitances C_1 and C_2.

V_H, B	6.0	6.1	6.2	6.3
V_{br}, кВ	> 45	42	24	17
V_{br1}, кВ	> 45	32	20	14
V_{br2}, кВ	20	10.5	9	6
V_{Acr}, кВ	34	17.8	15.9	10.2

The static breakdown voltage of the upper section of the device is higher than that for the lower section. Then when we increase the voltage V_0, the prebreakdown current initially appears in the lower section. In the conditions of absence of the resistive divider R_1-R_2, we revealed that the prebreakdown current leads to effect of redistribution of the anode voltage over the sections. The essence of the effect can be illustrated, for example, by the data shown in the column V_H = 6.1 V.

When the anode voltage approaches to V_{Acr} = 17.8 kV, the prebreakdown current starts flowing in the lower sections. This means that certain resistance of the discharge R_d is connected in parallel with capacitance C_2. The capacitance is discharged via R_d, so that the voltage V_1 decreases and the prebreakdown current disappears. We have the situation when the voltage V_2 turns out to be lower than V_{br2}. Further increasing of the anode voltage results in stabilization of the voltage V_2 and an increase in the voltage V_1. The breakdown occurs when the static breakdown voltage is achieved both at the upper and lower sections. Due to this effect the maximum possible breakdown voltage of the device is realized ($V_{br} = V_{br1} + V_{br2}$).

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MECHANISM OF HIGH EFFECTIVE GENERATION OF ELECTRON BEAMS IN HIGH-VOLTAGE DISCHARGE IN HELIUM AND ITS MIXTURES WITH NITROGEN AND OXYGEN.*

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High-voltage discharges in helium and its mixtures with oxygen for a long time are used to generate electron beams (EB) in medium-pressure gases. Nevertheless, the question of the most important properties of such discharges, in particular, the current-voltage characteristics, the efficiency of the generation of electron beams, the mechanisms of electron emission from cold cathodes, and the effect of helium purity on these parameters are debated up to this day. In this report, studies of the current – voltage characteristics and the efficiency of generation of EB in discharges in helium and its mixtures with nitrogen and oxygen have been conducted.

Studies were conducted in carefully outgassed cells with helium of purity no worse than 99.999%. It turned out that under these conditions, the I – V characteristic with a pressure of more than 10 Torr, as the voltage rises, realizes an exponential law of the I – V characteristic, then slows down its growth until a falling portion is obtained, and at a voltage higher than 1.5 kV, the rapidly increasing characteristic with current density $I = U^y$ with the value of y = 5-15. The appearance of the current – voltage characteristics in the initial region is explained by the exponential dependence of the Townsend multiplication factor α on the voltage U. As U increases, the growth of α slows down, passes a maximum, and then α rapidly decreases. The emission of electrons in the initial segment is carried out under the action of ions, metastable atoms and photons and weakly depends on U. At U> 500-600V, electron runaway from the cathode fall region begins to play a significant role, which, together with the fall of α, leads to a fall in the IVC. At U> 1.5 kV, an electron beam is formed, the photo-illumination of the cathode by resonant VUV radiation is amplified, and the current – voltage characteristic again acquires a rapidly increasing character. At U> 3.5kV, due to the predominance of photoemission, the efficiency of generation of EBs reaches 85%.

The introduction of oxygen or nitrogen in small quantities (less than 2%) dramatically increases the discharge current --- up to two orders of magnitude and, at a helium pressure of less than 4 Torr, increases the efficiency of generation of EF. This increase is associated with a large value of <γ> - kinetic emission under the action of fast molecular particles. In turn, the high value of <γ> is due to the interaction of fast heavy particles with the surface layers of cathodes doped with these particles. The results obtained make it possible to interpret from the unified point of view the entire diversity of the I – V characteristics in the discharges both in pure helium and in mixtures with molecular gases and to determine the conditions for achieving highly efficient generation of EB.

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FEATURES OF THE DISCHARGE DEVELOPMENT UNDER THE ACTION OF A TRIGGER PULSE IN THE TRIGGER UNIT OF SEALED-OFF COLD-CATHODE THYRANRON*

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Currently, high-current switching devices based on low-pressure hollow-cathode pulsed discharge (so-called pseudospark switches) are widely used [1-5]. The design and principle of operation of these switches are close to those of a classical hot-cathode hydrogen thyratrons. However, these devices do not have a hot cathode. Therefore, pseudospark switches are often called cold-cathode thyratrons or thyratrons with a grounded grid [6–8].

As in the case of classical thyratrons, a range of operating pressures of the switch corresponds to the left branch of Paschen's curve. Under these conditions the electron free path for ionization is much in excess of the electrode separation. For both self-breakdown of the main gap of the thyratron and for external discharge triggering a considerable pre-breakdown electron current is required [6-8]. For the case of external triggering, this current is provided due to a special trigger unit that is placed in the main cathode cavity. Various types of the trigger units are presented, for example, in [2, 9, 10].

By now, the sealed-off metal-ceramic devices have been developed and manufactured. The first devices have been described in the review [9]. Currently, these devices are commercially produced in the Pulsed Technology Ltd. (Ryazan, Russia, http://www.pulsetech.ru). Different triggering methods have been employed in these devices. In particular, in the thyratrons of the TPI type, the trigger unit is based on an auxiliary glow discharge [2, 10].

The operation conditions of the auxiliary glow discharge substantially affect the thyratron characteristics as a whole [10-13]. In particular, this concerns the breakdown voltage, the time delay of breakdown in the main discharge gap with respect to the triggering pulse, and the pulse repetition rate. Therefore, considerable attention is paid to the choice of the operating modes of the auxiliary discharge and the design of the electrode system of the device.

In this report, the results of investigation of sealed-off prototype of cold-cathode thyratron with modernized trigger unit are presented. As a distinct from the commercially produced sealed-off thyratrons, in the thyratron under investigation electrodes of the trigger unit represents two cups, faced to each other by open sides. As a result, auxiliary glow discharge ignition occurs over the "long path" and suitable discharge burning and ignition voltages are provided. Different schemes of auxiliary discharge powering and triggering schemes were tested. Features of the auxiliary discharge development under the action of a trigger pulse were investigated.

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EFFECT OF STREAMER VELOCITY ON THE CHARACHTERISTICS OF DYNAMIC DISPLACEMENT CURRENT*

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Currently, great attention is paid to research of streamer discharges in non-uniform electric fields [1–3]. Despite significant progress, there are still many unexplained phenomena and effects. It is known that breakdown in the gap with a high level of overvoltage occurs as a result of propagation of a large-sized streamer (ionization wave) [2, 4]. In this case, when the streamer is formed and moves along the gap, the current caused by the redistribution of the electric field (dynamic displacement current, DDC) flows through it [4]. It is evidently that the rate of the redistribution of the electric field should be determined by the propagation velocity of the streamer and the change in its shape. Therefore, the DDC magnitude is related to the streamer velocity. The results of the simulation aimed at finding the relationship between the dynamic displacement current and streamer velocity are presented in this study. The simulations were performed with the KARAT code [5], based on the analytical axisymmetric model of the conductive channel moving at a given velocity [6] and having a finite conductivity. The xoopic code [7] was used to verify the model. The actual parameters (dimensions and velocity) of a conductive channel estimated from the experimental data obtained using a four-channel ICCD camera was used in the simulation. An experimental setup (diode, detectors, etc.) used in the analytical estimates and modeling, completely repeated that used in the experiment. The analytical model confirmed the experimentally observed fact: the flow of significant current in a circuit and the voltage drop across a diode, depending on the parameters of the conductive channel. In the moving cathode model, the start of the channel motion and the time instant corresponding to the gap bridging were selected in accordance with the experimental dynamic displacement current waveform. The result obtained with the KARAT code is presented in Fig. 1a. The calculations were performed for two modes: constant V_{const} and dynamic V_{dyn} speed of a moving channel (Fig. 1b). The results of simulations (V_{dyn}, Fig. 1a) performed with the model implying the dynamic streamer velocity confirm the experimentally observed features of streamer motion in a “point-to-plane” gap, as well as the corresponding voltage drop across the diode and the DDC magnitude.

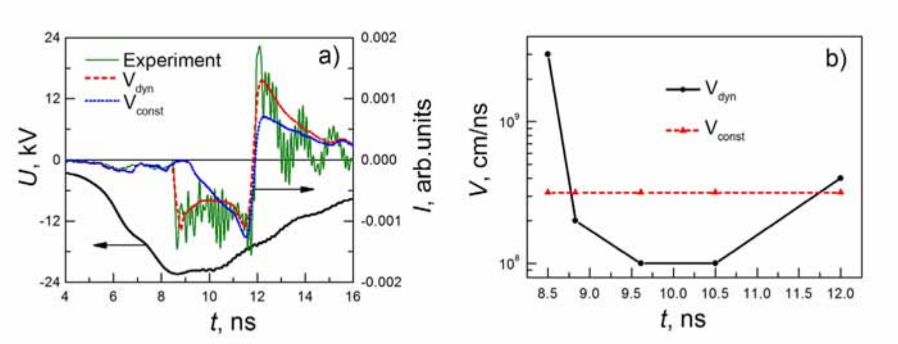

Fig. 1. a) Waveforms of the voltage across the gap, the dynamic displacement current obtained in experiment, as well as the dynamic displacement current obtained in simulations: V_{const} – model with the constant streamer velocity; V_{dyn} – model with the dynamic streamer velocity. b) Streamer velocities. V_{dyn} – dynamic streamer velocity; V_{const} – constant streamer velocity.

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RESISTANCE OF SPARK CHANNELS IN AIR IN UNIPOLAR AND OSCILLATORY DISCHARGES [*]

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Spark gaps are often used to commute energy at discharge of a capacitive storage on a load [1-3]. An understanding of the way in which the resistance of the spark channel varies as a function of time is important, not only for better comprehension of gas discharges but also in various applications where electric sparks are used as fast switches [4]. However, the experimental data available in the literature on the temporal variation of the resistance of spark channels are scanty [5]. Moreover, in most of these studies, the current pulse durations are shorter than 10 μs. It was shown in [3] that the switch energy losses provide critical impact on the overall circuit efficiency. A detailed review on existing models for spark resistance is given in [5] also. A vast majority of models are outdated and describe more or less only the resistance on a rising part of the current pulse. In some applications oscillatory regime (underdamped sinusoidal) has to be realized for the capacitor bank discharge, in particular, for a pulsed electromagnetic forming technology [6]. In this paper the arc resistance measurements have been done for new geometry of coaxial switch with closed loop rotating arc. Different operations regimes have been investigated with wide variation in the current-voltage amplitudes and pulse duration (up to 3 ms). 1D arc model has been developed for calculation of the arc resistance, valid for both the oscillatory and unipolar regimes of capacitor bank discharge. The results of numerical calculations are compared with experimental results.

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STREAMER START OF APOKAMPIC DISCHARGE*

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The apokampic discharge is a relatively new object of research, useful for laboratory modeling of transient light phenomena of the middle atmosphere [1-3] and potentially interesting for the development of plasma technologies for various purposes.

As our studies have shown, at pressures of ~ 400 Torr, several thousand breakdowns of the discharge gap are required to form an apokamp, which was due to with the need to heat the discharge channel. In addition, at low air pressures (100–450 Torr), glow traces were observed, resembling in form streamer coronas, the appearance of which preceded the apokamp grow. The article purpose is to investigate this phenomenon in detail and formulate a hypothesis about the streamer coronas effect on the apokamp development at low air pressures.

A pulsed discharge was ignited between steel pointed electrodes located at an angle of 140º relative to each other. One electrode was high-voltage, and the second had a capacitive decoupling with the ground. The power source provided a voltage pulse with an amplitude of $8 < U_p < 13$ kV and a pulse repetition frequency of $30 < f < 50$ kHz.

The electrodes were placed in a flask, the pressure in which could be adjusted from 760 to 80 Torr. The time course of the voltage was recorded near the electrode with capacitive decoupling using a capacitive divider, and the current between the electrodes was a shunt. The signals from the divider and shunt were fed to a TDS-3034 oscilloscope (Tektronics, Inc.).

A typical apokamp formation scenario under the conditions of our experiment was as follows: when five to ten voltage pulses are applied to the electrodes, a pulsed spark discharge is ignited in the gas discharge gap. With the subsequent increase in the number of pulses N, a discharge channel is formed, an increase in its diameter and bending occurs. When the number of pulses $N \geq 1500$, an apokamp is formed at the site of maximum bending.

The decrease in pressure entails an increase in the length and an increase in the intensity of the streamer coronas, which means that ionization increases in the space between them. It is also noted that when the pressure changes to the larger side, the streamer coronas are displaced by the bases closer to the point of maximum bending of the channel, and when it is lowered, they are similarly shifted towards the electrodes. Consequently, the larger the p, the higher the probability of formation of the apokamp (with a fixed U_p) without participation of the streamer coronas as an intermediate stage.

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COMPUTER SIMULATION OF HIGH CURRENT VACUUM ARC WITH DEVELOPED ANODE SPOT *

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High current vacuum arc (HCVA) is an arc with current in the order of several kiloamperes. Such kind of arcs is typical for vacuum interrupters or circuit breaker. At the moderate current, the main source of plasma in HCVA is multiple cathode. However, when the current increases to a certain threshold value, the anode becomes another plasma source. The bright, well defined spot appears at the anode surface. This phenomenon is known as the anode spot [1]. Unlike the cathode spot, there seems to be nothing mysterious about the anode spot operation. Anode surface is heated by heat flux from the interelectrode plasma up to a temperature at which the saturated vapor pressure becomes higher than the total pressure of near-anode plasma. After that, the anode vapor starts to flow into the interelectrode gap, where the vapor is rapidly ionized. A dense relatively cold plasma blob appears at the anode as a result of the mentioned processes. The plasma blob temperature is considerably smaller than the interelectrode plasma temperature, the density of plasma blob is much higher than the interelectrode plasma density and the average charge state of the blob ions is about one. Thus, the anode plasma blob looks much brighter than the interelectrode plasma (Fig.1).

The processes described above were self-consistently modeled using a hybrid model based on that developed earlier [2] (Fig. 1). The hybrid model allows to direct simulate the evaporation (including Knudsen layer), ionization and charge exchange. The results obtained in the framework of the model are consistent with the known experimental results at least qualitatively.

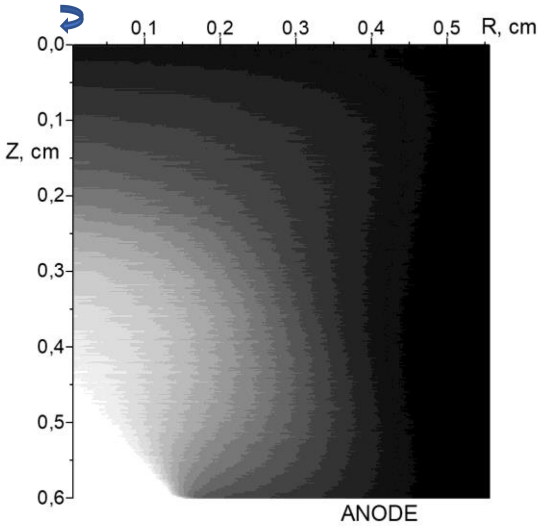

Fig. 1. Calculated HCVA appearance at the stage of well-developed anode spot. Arc current is 2 kA, surface temperature in the anode center is about 2.1 kK.

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MODELING OF PLASMA JET OF VACUUM ARC WITH COPPER-CHROMIUM CATHODE UNDER ACTION OF STRONG AXIAL MAGNETIC FIELD *

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The high-current vacuum arc (HCVA) with composite copper-chromium electrodes is appeared in vacuum interrupters with external axial magnetic field (AMF), which are widely used in the world. Thus, the measurement and modeling of the plasma properties those are typical for interelectrode plasma of HCVA with AMF is in high demand. Recently [1], ion charge state composition of HCVA plasma in the dependence on time, average current density and AMF was measured. It was found that the ion average charge state comparatively weakly depends on the average current density. The average charge state increases with the AMF increase as expected, but for AMF more than 0.8 T, the increase in the charge state slows down.

It is known that the plasma of HCVA under the action of AMF greater than 15-20 mT/kA consists of unmixed plasma jets emitted by separate cathode group-spots. Thus, in order to obtain the plasma parameters typical for HCVA with strong AMF is enough to simulate a single plasma jet originated from the cathode group-spot. The present paper is devoted to computer simulation of the plasma jet emitted from one group-spot on composite coper-chromium cathode in a strong AMF, taking into account the secondary plasma arising from the sputtering of electrodes and the incomplete sticking of the incident ions. Using the previously developed hybrid model [2], the generation of secondary plasma and the interaction of the secondary plasma with the plasma emitted by the cathode spot were studied. It was shown that secondary plasma considerably influences on the parameters of the primary plasma including ion charge composition. The plasma parameters of the jet calculated in the framework of the model is qualitatively consistent with the experimental data.

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ON POSSIBLE REASONS OF POSITIVE NEAR-ANODE VOLTAGE DROP IN HIGH-CURRENT VACUUM ARC*

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There are experimental evidences that under certain conditions a positive anode voltage drop occurs in the near-cathode region of the high-current vacuum arc (HCVA) [1], although the exact location of the potential drop is not determined experimentally. Some researchers believe that this positive voltage drop is inside the anodic plasma sheath [1, 2], moreover, they suggest that this positive drop is the cause of the anode spot appearance. However, in [3, 4] it is shown that for the plasma parameters typical for HCVA the anode voltage drop inside the anode plasma sheath remains negative even at a current density higher than the electron thermal current density. The reason for that is the formation in the near-anode plasma of the electron shifted Maxwell distributions with the velocity shift corresponding to the electron current velocity. At this condition the anode plasma sheath voltage drop remains negative at any current. Despite this conclusion the positive near-anode voltage drop formation is still possible. This may not necessarily be a voltage drop in the sheath. A geometric-ohmic voltage drop in the thin near-anode plasma layer aroused due to current constriction is also possible. In this paper, MHD and kinetic approaches have been used to study various possible scenarios for the formation of the positive voltage drop both in the anode plasma sheath and in the near-anode plasma region of HCVA. In particular, it was demonstrated the formation of the positive voltage drop in the anode plasma sheath when the radius of current constriction become less than the electron coulomb collision mean free path.

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SIMULATION OF THE GENERATION OF JETS AND DROPS BY THE CATHODE SPOT OF A VACUUM ARC*

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The explosion of liquid-metal jets produced during the formation of a crater on the cathode of a vacuum arc is the basic mechanism of the initiation of individual cells in the cathode spot [1]. To analyze the processes involved, a two-dimensional axisymmetric model is proposed that describes the generation of quasi-one-dimensional liquid-metal jets during the growth of azimuthal instability of the liquid-metal rim of a cathode microcrater [2, 3]. The simulation input data are the jet diameter, propagation velocity, and temperature, which are calculated using a previously developed semiphenomenological model of crater formation [4]. In the context of the proposed model, the jet formation has been simulated for different modes of melt splashing from a crater [5] without considering the jet interaction with the cathode spot plasma. It has been shown that in the "active splashing" mode, a jet of almost constant diameter, longitudinal velocity, and temperature is formed. The head of the propagating jet transforms into a spherical drop due to surface tension. This is accompanied by the excitation of a capillary wave, which propagates to the jet base and harmonically modulates its diameter. In the "inertial splashing" mode with the melt velocity near the jet origin decreasing with time, a jet with a longitudinal velocity gradient is formed. The velocity gradient acts to elongate the jet (reduce its diameter) and causes the drop-shaped head to separate away from the jet and the entire jet to break away from the crater. As the jet further propagates, it breaks into drops. It has been demonstrated that the jet breakup and its breakaway from the cathode are due to the Rayleigh–Plateau instability that occurs when the length of the modulated jet becomes equal to a capillary wavelength satisfying the instability criterion.

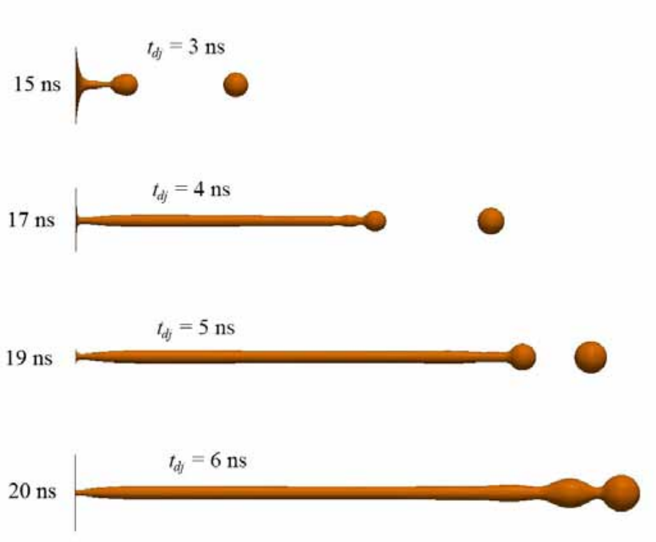

Fig. 1. Jet disintegration into drops and its separation from the crater in the inertial melt splashing mode.

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MODEL OF THE CONVECTIVE THERMAL DESORPTION OF DEUTERIUM AND FORMATION OF PLASMA ION COMPOSITION IN A PULSED VACUUM ARC DISCHARGE WITH A METAL DEUTERIDE CATHODE*

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Although the development and use of neutron tubes with arc source of deuterium ions has been developed for nearly half a century, the mechanism of desorption of hydrogen isotopes from deuterated cathode in arc discharge is not studied yet. Today, it is considered that the main suppliers of deuterium ions in plasma of arc source are cathode spots [1]. In this work the numerical model based on the cellular structure of the cathode spot of a vacuum arc has been developed to describe the process of desorption of deuterium and the formation of the ion composition of plasma of a vacuum arc source with a $ZrD_{0.67}$ cathode (see Fig. 1). It was shown that deuterium and zirconium are almost completely ionized in the plasma jet of the cell at a distance of ~ 10 μm from the cathode. In this case, the number of deuterium ions in the mixture of deuterium ions and all zirconium ions is determined by their atomic fluxes from cathode craters and is ~ 44%. However, taking into account the desorption flow from the periphery of cathode spot cells and ionization in the plasma of the group cathode spot, this value can reach ~ 80%.

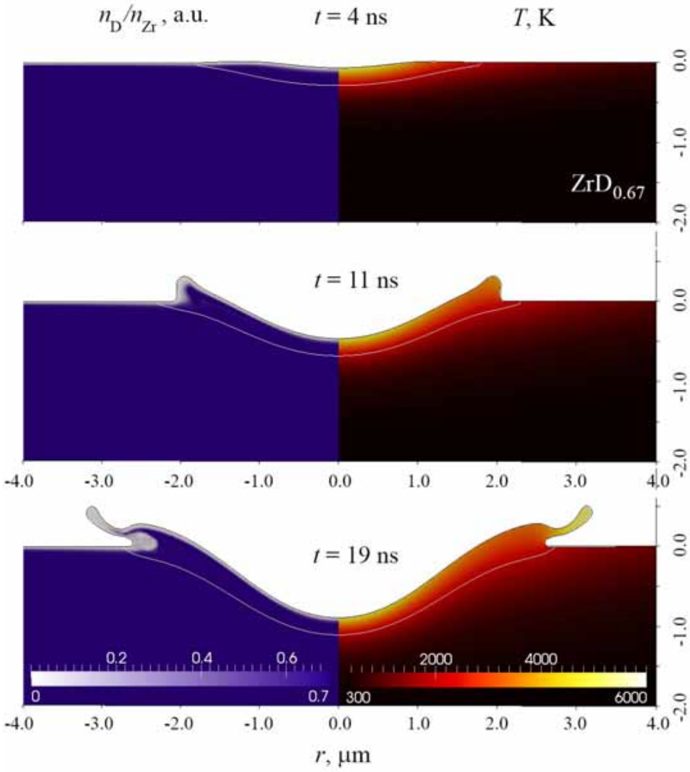

Fig. 1. Temperature distribution and deuterium concentration in the $ZrD_{0.67}$ cathode during the crater formation.

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A HIGH-CURRENT PULSED VACUUM ARC PLASMA SOURCE*

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The vacuum flashover discharge is intensively explored for a long time [1]. It acts as a source of multiply charged plasma [2]. The results of the plasma ion flow study with high temporal resolution and the electrode erosion dependences on the amplitude of the current pulse are presented in the research. A coaxial plasma source with a 1 mm distance between the cathode and the anode was used. The cathode was made of copper and had a diameter of 2 mm. Steel and molybdenum were used as anode materials. Anode ring with a diameter of 2 cm has a 2 mm outlet. Polyethene was used as a dielectric. The plasma source was placed in a vacuum chamber, which was pumped to a pressure of about 10^{-4} mm Hg. In order to make a vacuum arc, a pulse generator based on a system of capacitors was used. The generator can create pulses with an amplitude of up to 12kV and a half-height duration of 10μs.

Plasma parameters were taken using two identical probes connected with an oscilloscope. This method allows analyzing both the spatial and temporal structure of the ion flow. The probe was in a grounded housing with an input aperture of 9 holes with a diameter of 200 μm. The collectors were located at a distance of 15 cm and angles of 0°, 15°, 30°, 45° and 60°. For each combination of parameters, an averaged waveform was obtained. It was also carried out numerical integration over the angles to calculate the total ion current fig 1.

The main ion flow reaches the detector in 3.5 μs. Almost all ionic current is distributed in solid angle up to 60°. The maximum current density is achieved at an angle of 30° for the steel anode and at 0^0 for molybdenum. The presence of a strong peak in the ion current oscillograms reveals the formation of an intense plasma wave directly behind the leading front of the expanding plasma.

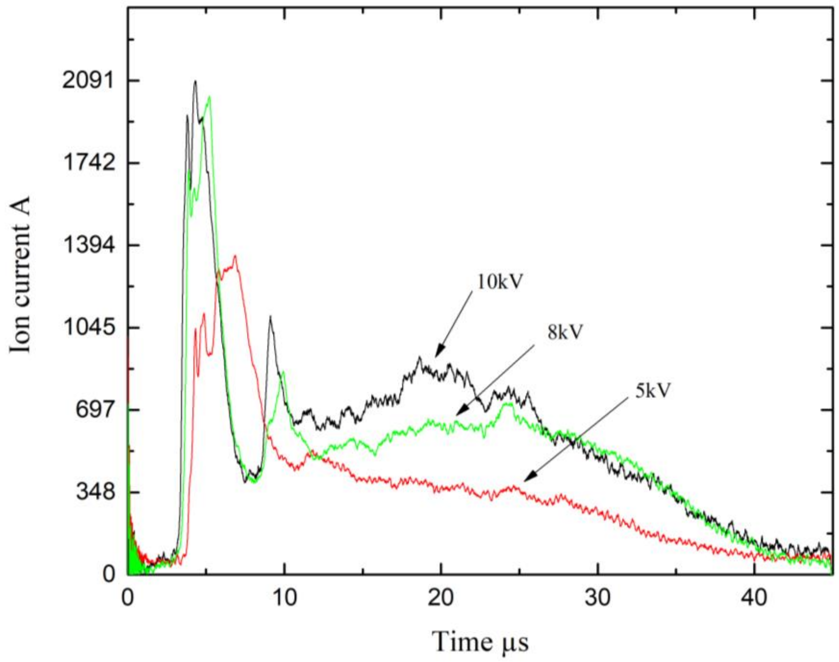

Fig. 1. Integral ion current dependence through the surface of a hemisphere with a diameter (15 cm) on time, Mo anode.

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ABOUT LIMITATIONS IN HYBRID MODELS APPLICATION FOR STUDY OF AN ELECTRONS AVALANCHE IN PULSED GAS DISCHARGE OF HIGH PRESSURE*

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The paper analyses the details of the application of the hybrid model for calculation of the formation of high-pressure gas discharge in conditions where the transition of electrons into runaway mode is possible. Usually in hybrid models, PIC-MC method is used only for calculation of runaway electrons, and the standard hydrodynamic approach is used for calculation of plasma electrons. However, electron concentration is low at the initial stage of discharge formation, so application of hydrodynamic model is incorrect because the motion of individual electrons is crucial until the avalanche reaches critical size. In this paper, the characteristics of such motion are investigated using Monte-Carlo simulation in 3D-configuration to estimate limitations of hybrid model application. The investigation is important for correct description of initial stage of high pressure pulsed discharges and for calculation of electron transition into runaway mode.

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INVESTIGATION OF PLASMA ION COMPOSITION GENERATED BY HIGH-POWER IMPULSE MAGNETRON SPUTTERING (HIPIMS) OF GRAPHITE*

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Amorphous carbon diamond-like (DLC) films are characterized by a high content of diamond-like C-C bonds (70-90%) that explains their high hardness (up to 50 GPa), high IR transparency (up to 90%) and other properties [1]. Diamond-like coatings are deposited by vacuum-arc cathode sputtering, pulsed laser deposition, deposition from an ion beam (i.e. by methods creating high-density carbon ions flow), but all these methods do not allow the deposition of amorphous carbon (a-C) films on large-area substrates. In the case of magnetron sputtering of graphite, it is possible to deposit a-C coatings on large-area substrates, however, the plasma produced in this case has a low (less than 10%) degree of ionization, and the resulting films have a low hardness (5-10 GPa) even with a negative voltage bias applied to the substrate [2]. High-power impulse magnetron sputtering (HiPIMS) used to increase the density of the plasma produced in this case (up to 10^{13} cm^{-3}) and the fraction of ionization of sputtered material – carbon (up to 70 %) [3]. It makes possible to increase the ion bombardment of the growing film by applying a negative bias HF potential to the substrate, which allows deposition of DLC coatings.

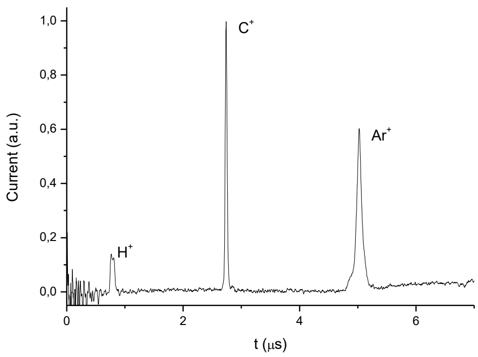

Fig. 1. Output signal of time-of-flight analyzer for HiPIMS of graphite at the discharge current of 30 A, pressure of 1 mtorr, pulse duration of 22 μs, and ion accelerating voltage of 15 kV

Parameters of plasma, generated by HiPIMS of graphite, depend on properties of magnetron discharge. In [4] it was shown, that self-sputtering of graphite characterized by abrupt increase of discharge current. It can be related to change in the plasma ion composition: carbon ions should be the majority. The purpose of this research was to measure the ion composition of plasma during HiPIMS of graphite. To measure it, a linear axially-symmetric time of-flight spectrometer with flight length of 1.2 m and radial focusing of analyzed ions, having a secondary electron multiplier detector was used. Output signal of the time-of-flight analyzer depends on discharge parameters – argon pressure, discharge current and pulse duration. In figure 1, one can see dependence of current of time-of-flight analyzer on time from analysis start and its interpretation. For the discharge current of 30 A and argon pressure of 10^{-3} Torr the particle fractions are the following – H^+ is 9%, C^+ is 33%, Ar^+ is 58%. Increase of discharge current to 70 A leaded to growth of C^+ fraction up to 60% that results from more intense sputtering of the graphite cathode. This trend was observed both for 20 μs and for 30 μs pulse width. Decrease of argon pressure down to $3\cdot10^{-4}$ Torr leaded to reduction of C^+ fraction down to 13%, which is related to less intense sputtering. Thus, using of time-of-flight analyzing of plasma ion composition generated by HiPIMS of graphite one can choose optimum discharge pressure and current – both of them should be maximized.

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SPUTTERING KINETICS OF GRAPHITE TARGET IN HIGH-POWER IMPULSE MAGNETRON DISCHARGE* (HIPIMS)

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Magnetron sputtering makes it possible to deposit coatings on substrates of a large area, since magnetron systems can be extended (up to 3 m), and the substrate can be scanned. That makes magnetron sputtering more technological procedure than vacuum-arc evaporation or laser sputtering of materials. However, the plasma produced in this case is characterized by a small (less than 10%) degree of ionization of sputtered material. Therefore, the deposited coatings have a columnar and porous structure [1], and in the case of graphite sputtering the deposited amorphous carbon (a-C) films are graphite-like and have a hardness of 5–10 GPa even when negative bias is applied to the substrate [2]. Pulsed high-power magnetron sputtering (HiPIMS) is used to increase the density of the resulting plasma (up to 10^{13} cm^{-3}) and the degree of ionization of the sputtered material (up to 30-50%). This allows increasing the ion bombardment of the growing film when a negative bias potential is applied to the substrate to overcome the above disadvantages. Unfortunately, the consistent theoretical model of pulsed high-power magnetron sputtering (HiPIMS) materials has not been proposed yet. It is the task of this work.

Here the original zero-dimensional theoretical model of a magnetron high-current discharge (used in HiPIMS) is formulated. When modeling, the dense plasma region near the cathode and the vast plasma region in the volume of the magnetron chamber will be artificially separated. The main theoretical task is to simulate a dense plasma that forms the plasma-chemical composition, while the surrounding plasma can be described in terms of the well-known complementary model of Brenning [3].

The proposed theoretical approach based on a nonstationary spatially averaged (zero-dimensional) model of the region of intensive ionization of a magnetron discharge [4]. It accounts for the dynamics of electrons, neutral atoms and positive single charged ions of carbon and argon. To consider the plasma composition accurately we implement large number of low-pressure plasma-chemical bulk reactions (impact electron ionization, Penning processes, diffusion, recharging, etc.) as well as boundary reactions (losses at walls). At the mathematical level, the model consists a set of particle balance equations and the electron temperature balance equation describing the behaviour of quasi-neutral multi-component HiPIMS discharge plasma. Main result of theoretical simulation is the estimation of optimal parameters for the experimental setup intended for obtaining a dense plasma with the desired composition.

Theoretical work is complemented by the experimental measurements of plasma parameters and ion composition using the Langmuir probes and the time-of-flight spectrometry.

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TEMPERATURE GRADIENTS IN TARGETS WITH HIGH-INTENSITY IMPLANTATION AND THEIR INFLUENCE ON THE CHARACTERISTICS OF ION-MODIFIED LAYERS*

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This paper is devoted to the study of the gradient temperature field dynamics and distribution in the metal targets irradiated with high-intensity beams of gas and metal ions. The investigations concerned ion implantation modes with the ion beam current density from several tens of mA/cm^2 up to A/cm^2 were investigated.

The ion beam power was additionally varied due to the change of ion energy in the range from 0.6 to several keV and the pulse duty factor in the range of 0.2–0.8. The integral temperature of the target was measured with an electrically isolated thermocouple. To measure the dynamic change in the local temperature on the irradiated target a high-temperature pulse pyrometer KLEIBER 740-LO was used.

The problem of temperature evolution and metal sample melting under the exposure of a high-intensity repetitively pulsed ion beam was solved numerically using the heat conduction equation written in cylindrical coordinates.

Analysis of the experimental data obtained with the use of electrically isolated thermocouple, pulse pyrometer, and numerical simulation revealed the presence of significant gradient temperature fields both over the surface and along the depth of targets irradiated by high-intensity ion beams.

* This work was supported by the grant of Russian Science Foundation (project No. 17-19-01169)

INSTANT VALUES OF THE MAIN PLASMA PARAMETERS OF THE NON-SELF-SUSTAINED ARC DISCHARGE WITH THERMIONIC CATHODE *

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The probe studies of the plasma of a non-self-sustained gas arc discharge was carried out. Plasma generation by a generator "PINK" with a combined thermionic and hollow cathode [1] was carried out. The plasma parameters were studied using a single cylindrical Langmuir probe. The instantaneous values of the electron concentration and temperature, as well as the plasma potential, are obtained. The dependence of the basic plasma parameters not only on the characteristics and conditions of discharge burning (discharge and cathode heating currents, discharge voltage, operating pressure, gas), but also on the phase of the cathode heat current is shown.

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EFFECT OF THE DISCHARGE AREA MAGNETIC FIELD ON THE MASS-CHARGE COMPOSITION OF TWO-COMPONENT ION BEAM*

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The use of the cathode consisting of two metals in the vacuum arc ion source allows the generation of two-component ion beams. The generation of two-component metal ion beams in the vacuum arc source was investigated using a copper-chromium cathode as model material [1]. In this paper the investigation of the effect of up to 1 T induction axial magnetic field generated in the discharge region of the ion source with the copper-chromium cathode on a mass-charge composition of the ion beam. The magnetic field application is shown results in the charge state increase for the both metals in the cathode. The ion beam current increase at the constant discharge current in the presence of the magnetic field is shown to be associated with the focusing of the plasma flux along the magnetic field lines during the magnetization of plasma electrons and the retention of ions by the potential of negatively charged plasma. When the magnetic field is applied, a ratio of the copper and chromium ion proportion was found to be corresponded to the ratio of their atoms in the cathode of the vacuum arc source. The presented results may be useful in practice, for example, to the discharger electrode surface modification by creating copper-chrome cover with different atomic proportions.

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SIMULATION OF ELECTRON BEAM GENERATION WITH A CONSTANT, RISING AND FALLING BEAM POWER DURING ITS PULSE*

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To generate pulsed (hundreds of microseconds) intense (hundreds of amperes) electron beams, two methods are most often used to apply a high voltage to the accelerating gap: 1. Using a high-voltage artificial forming line, the energy from which is completely taken during the beam current pulse; 2. The use of high-voltage capacitor battery with its partial discharge. The second method is most popular due to the possibility of generating an electron beam with a wider range of pulse durations. However, when using a high-voltage capacitor bank and a constant amplitude of the beam current, the voltage across the accelerating gap has a linearly falling shape, and, therefore, the power of the electron beam is linearly decreased during its pulse. Most often, attention to this phenomenon is not emphasized, since with the electron energy in the beam varying in the range of 10–30 keV, their depth of penetration is substantially less than the depth of impact of this beam on any inorganic material (units of microns Vs hundreds of microns). In the material science calculations, the electron energy is most often assumed to be constant, and accordingly, it is considered that the beam power is also constant during the pulse, and the change in the accelerating voltage can be neglected. However, such an assumption can be made not always, since in intensive modes the accelerating voltage can change by 50% or more.

In this work, the operation of an electron source with a plasma cathode was simulated, where a capacitor battery is used as a high-voltage generator. The calculations were performed with the aim of obtaining an electron beam, the power of which is either constant during its pulse, or has a linear increase or decrease.

The calculations confirm the uniqueness of plasma electron sources, and also open up additional possibilities for the use of such sources for both scientific and technological purposes.

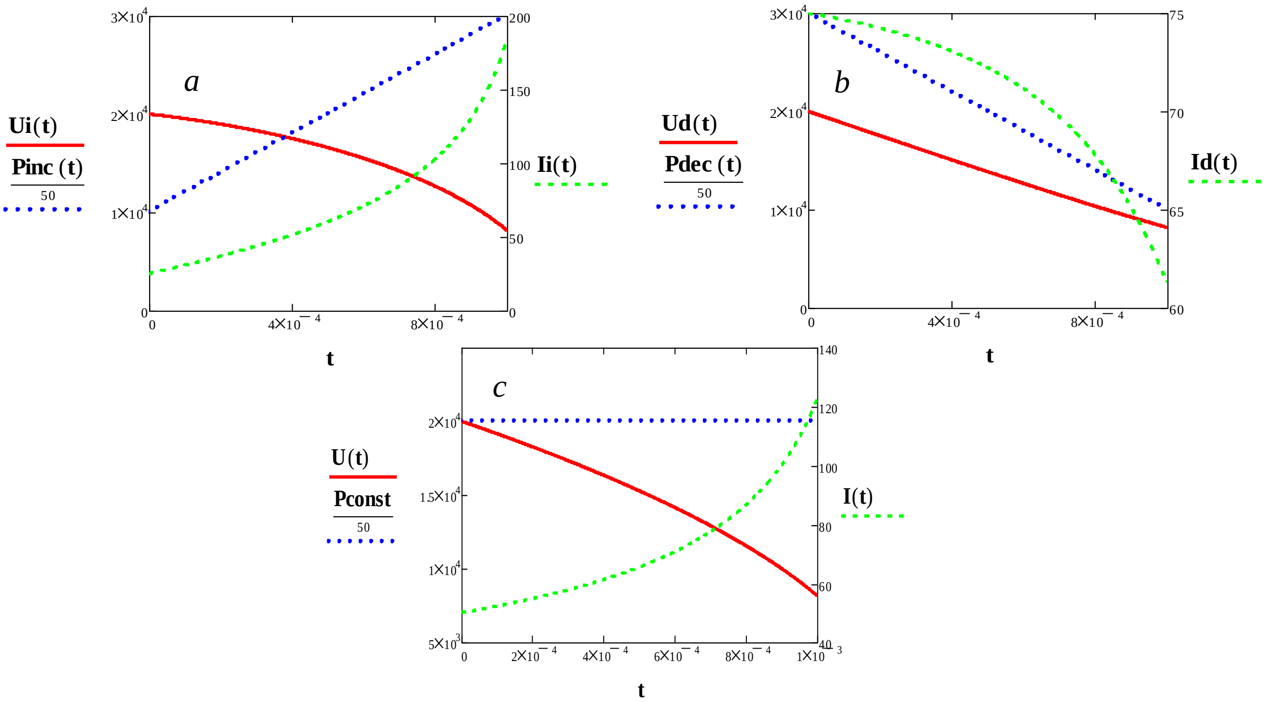

Fig. 1. Oscillograms of the currents and voltages of the capacitor to obtain the rising (a), falling (b) and constant (c) power at the load with a total energy of the beam content of 1 kJ by duration of 1 ms.

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MEASUREMENT OF PLASMA PARAMETERS IN A HYBRID DC+HIPIMS MODE OF MAGNETRON SPUTTERING*

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Direct current (DC) magnetron sputtering is the most basic and inexpensive type of magnetron sputtering. But during DC magnetron sputtering the plasma concentration is low (about 10^9 cm^{-3}), and its ionic component is represented mainly by the ions of the working gas (Ar^+). In high-power impulse magnetron sputtering (HIPIMS) plasma density could be as high as 10^{12} cm^{-3}. However, a significant disadvantage of HIPIMS is the reduction in the films deposition rate compared to DC sputtering. Different ways have been offered to improve deposition rate, for example, pulse waveform modulation [1]. Another perspective approach is hybrid technology, known as hybrid DC + HIPIMS co-sputtering process [2].

In this work the plasma parameters in DC + HIPIMS mode of magnetron sputtering have been investigated. Hybrid mode (DC + HIPIMS) of the magnetron sputtering was realized at an average power of 500 W, applied to a planar magnetron with a Cu target. The main parameters that changed during the experiments, were frequency of high current pulses (100 Hz and 500 Hz) and average power of DC discharge in hybrid mode DC + HIPIMS. Wherein the total average discharge power and the duration of high current pulses are remained unchanged and were of 500 W and 100 μs, respectively. During the experiments such plasma parameters as electron energy distribution function, plasma density, electron temperatures, plasma and floating potential were measured with movable Langmuir probe. Typical waveforms of discharge voltage and current in HIPIMS (250 W, 500 Hz, 100 μs) + DC (250 W) mode at a pressure of 0.3 Pa are shown in Fig. 1,a. An example of the waveforms of the discharge current and the ion current per probe (bias voltage of -80 V) in the HIPIMS (500 W, 100 Hz) mode are shown in Fig. 1,b.

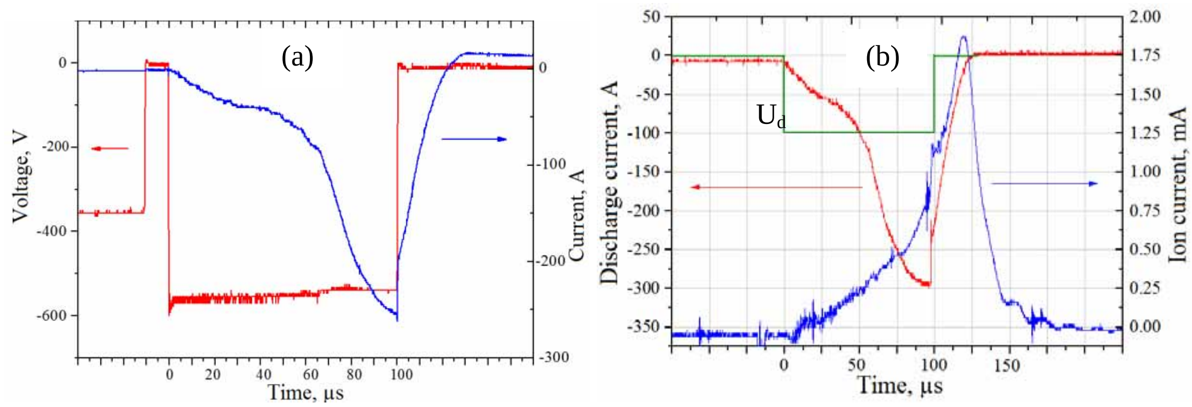

Fig. 1. Waveforms of discharge voltage and current in HIPIMS (250 W, 500 Hz, 100 μs) + DC (250 W) mode at a pressure of 0.3 Pa (a). An example of the waveforms of the discharge current and the ion current per probe (bias voltage of -80 V) in the HIPIMS (500 W, 100 Hz) mode (b).

It is shown that the electron density in the DC + HIPIMS mode is about 1-2 orders of magnitude higher than with DC magnetron sputtering. Moreover, it can be regulated by the frequency and amplitude of high-current pulses. During a high-current pulse in the plasma, the number of metal ions increases and the discharge goes into self-sputtering mode. This is confirmed by the change in the slope of the current-voltage characteristics of the discharge and the increase in the rate of growth of the discharge current on the oscillograms. The transition to the self-sputtering mode occurs when the discharge current reaches 50–100 A, which corresponds to a target power density of 350–700 W/cm^2. With a high content of metal ions in plasma, its electron temperature decreases due to the fact that metal atoms have much lower excitation and ionization potentials by electron impact than argon atoms.

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ABOUT CHANGES IN THE PHYSICOCHEMICAL PROPERTIES OF AQUEOUS SOLUTIONS USED AS A LIQUID ELECTROLYTE CATHODE*

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The gas discharge between liquid electrolyte cathode and metal anode was experimentally investigated. Aqueous solutions of sodium chloride, potassium chloride, sodium sulfate, sodium hydroxide, and potassium hydroxide were used as the electrolyte cathode. The experiments used the original approach, which was proposed in paper [1].

The essence of the experiments was as follows. The discharge was ignited and its combustion was maintained at a constant current (I = *const*). Stable discharge burning was provided by the use of inverter power supplies. The decrease in the aqueous solution was compensated by the addition of distilled water (solvent). The working volume of the aqueous solution during the combustion of the gas discharge remained unchanged (V_s = *const*). The volume of solvent added ΔV was comparable to the working volume of the electrolyte V_s.

In fig. 1 as an example, some results are presented. As can be seen, the specific electrical conductivity of aqueous solutions of alkali metal salts (sodium chloride, potassium chloride, sodium sulfate) increases, and alkali (sodium and potassium hydroxides) decreases.

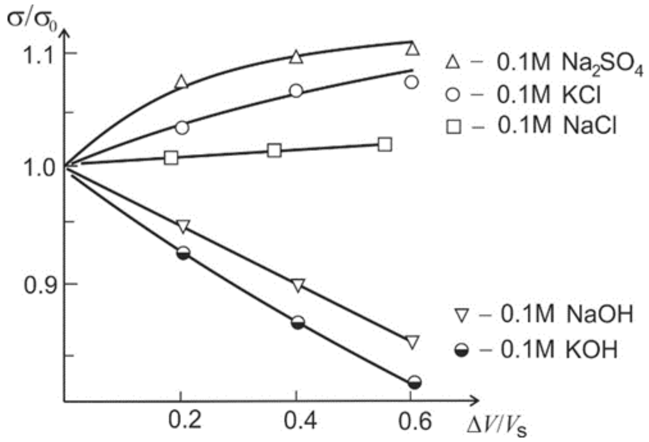

Fig. 1. Changes in electrical conductivity of aqueous solutions used as liquid electrolyte cathode. V_s = 5.0 l. I = 7.5 A.

In the experiments, alkalization of aqueous solutions of alkali metal salts (sodium chloride, potassium chloride, and sodium sulfate) was observed. The concentration of hydroxide ions in the aqueous solution increased. The solution was enriched with more mobile ions. This fact explains the increase in the electrical conductivity of aqueous solutions of alkali metal salts (sodium chloride, potassium chloride and sodium sulfate).

A decrease in the electrical conductivity of aqueous solutions of alkalis (sodium and potassium hydroxides) indicates of removing of sodium and potassium ions into discharge region.

Thus, it has been established experimentally that, despite significant solvent dilution, the specific electrical conductivity of aqueous solutions of alkali metal salts and alkalis varies slightly. The paper analyzes the mechanism of this phenomenon. The main elements of the mechanism were revealed: 1) drip removal of ions from the electrolyte due to cathode sputtering; 2) drift of positive alkali metal ions to the cathode and their return to the electrolyte; 3) alkalization of aqueous solutions of alkali metal salts.

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SOME FEATURES OF THE ELECTRIC DISCHARGE WITH THE ANODE AS A LIQUID ELECTROLYTE FLOW*

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Electric discharge between a liquid electrolyte anode and a metal cathode was experimentally investigated. Sodium chloride solutions in distilled water were used as electrolyte.

The aim of the work was to study the properties of electric discharge with liquid electrolyte anode at elevated currents. The study was conducted in the range of currents of 0.1-3.5 A. Electric power was supplied from a three-phase rectifier through a C-L-C filter.

Electric discharge was created with use of various embodiments of electrode assemblies.

In one embodiment, the body *1* of anode assembly was made of a dielectric material in the form of an elongated hollow body (fig.1). Inside the cavity was mounted metal electrode *2* from a palladium-tungsten alloy. The electrolyte flowed out of a narrow slot *3*, made on the housing *1*. The tubular metal cathode *4* was located coaxially with the anode housing in different positions: with horizontal displacement ($x \neq 0$) and without displacement ($x = 0$). The displacement of electrodes relative to each other contributed to the formation of a voluminous plasma *5*. As can be seen from the oscillograms *6*, presented, during the burning of the discharge, current and voltage pulsations occurred.

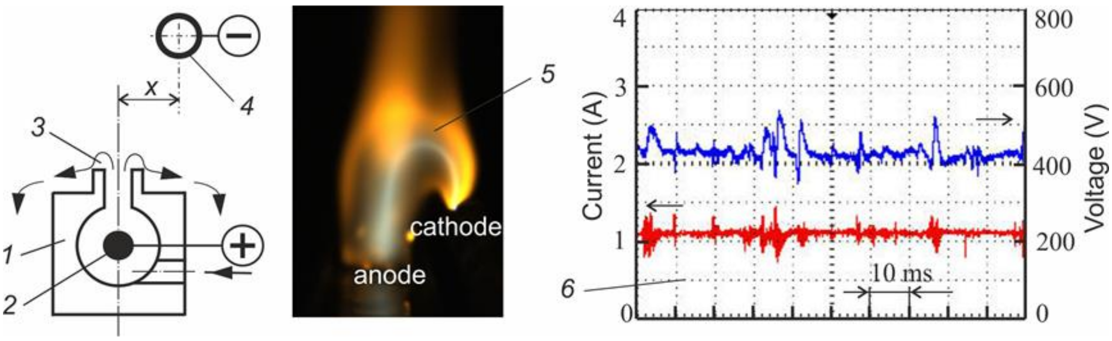

Fig. 1. Diagram of discharge assembly, photo of discharge, oscillogram of current and voltage. x = 14 mm. The molar concentration of an aqueous solution is 0.1 mol/l. Instant photo taken with exposure 0.2 ms.

In this case the peculiarities of electrical discharge which were shown with an increase in current and an increase in the interelectrode distance vertically were found, and also when the concentration of the aqueous solution was changing - an anode.

With an increase current in the discharge gap, a contracted channel was formed. It is noteworthy that contracted channel adjoined liquid anode without changing the brightness of the glow.

On the high-speed video frames contracted channel was in a single copy. With increasing discharge current channel was expanded. Spectral studies have shown that the radiation spectrum contains intense Balmer hydrogen lines. It can be noted that discharge radiation has common features with the emission of a plasma column near metal cathode in the water flow [1].

Increasing distance between electrodes was led to disruption of spatial stability of the plasma column. The physical picture of the phenomena was almost the same when using aqueous solutions with different concentrations.

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AXIAL DISTRIBUTION OF PLASMA ION COMPOSITION IN PLANAR MAGNETRON DISCHARGE*

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In a planar magnetron discharge with a target diameter of 50 mm the axial distribution of plasma ion composition was measured. The mass-to-charge measurements were made by using a modified quadrupole mass spectrometer. Experiments were carried out with copper target and argon as operating gas. The measurements were carried out along the magnetron axis at a distance from 10 to 30 cm from the target. The operating pressure varied in the range from $7\cdot10^{-4}$ to $2\cdot10^{-3}$ Torr at a magnetron discharge current from 50 to 300 mA. It is was shown that the distribution of argon and copper ions along the axis has a nonmonotonic character.

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PLASMA GENERATION DELAY ON THE SURFACE OF COPER AND DURALUMIN CONDUCTORS WITH DIELECTRIC COATING*

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Studies of the skin explosion of homogeneous and double-layer cylindrical copper and duralumin conductors with a dielectric coating of zirconium dioxide (ZrO_2) were carried out. Previously [1, 2] at the amplitude of magnetic field induction on the surface of a conductor up to 400 T, it was shown that due to the double-layer structure of a conductor with an outer layer of lower conductivity (copper and duralumin conductor with a deposited titanium layer) a significant plasma formation delay was observed for titanium layer thicknesses more than 20 μm. For the outer layer, it is possible to use other materials with more than 15 times lower conductivity and with sublimation energy, which is comparable with the sublimation energy of the electrode material in magnitude [3]. The conductivity of dielectric coatings is much less than that for any metallic, therefore it was expected to obtain large delays before the beginning of plasma formation at the surface with coating of lower thicknesses. The experiments were carried out on a high-current MIG generator with current amplitude up to 2.5 MA and a rise time of 100 ns. The plasma generated on the conductor surface was imaged using a four-frame optical HSFC Pro camera with a frame exposure time of 3 ns. The internal structure and density of the plasma on the surface of the conductor formed during an electrical explosion is supposed to be investigated using X-ray radiography. The X-ray radiograph was based on the use of the X-pinch with hν > 0.8 keV at exposure 2 – 3 ns. In addition, vacuum photoemission diodes recorded a surface plasma reaching a temperature of ~ 2 eV in the black-body approximation. The coating deposition was carried out on an ion-plasma QUINTA facility. Unfortunate The internal structure and density of the plasma on the surface of the conductor formed during an electrical explosion is supposed to be investigated using X-ray radiography. ly, the synthesis of dielectric coatings on the surface of metals with a large curvature (cylinder diameter 1–3 mm) led to the formation of internal stresses in the coatings and their cracking. Therefore, the deposition of zirconium dioxide films without cracks with a thickness more than 7.5 μm was not possible. Multilayered coatings with alternating layers of ZrO_2 (0.9 μm) and Zr (0.1 μm) were more crack-resistant. Due to technological complexity, we formed the coatings with layers number up to 16 for our experiments. A delay in the onset of plasma formation on a dielectric-coated part of the load of up to 70 ns was obtained with a field induction of up to 300 T compared with that for a pure copper or duralumin conductor. At the field increases to 350-400 T, the plasma formation delay decreases and it is about 30 ns.

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SIMULATION DIFFERENT SCENARIOS OF TRANSITIONS BETWEEN DIFFERENT MODES OF CURRENT TRANSFER TO ELECTRODES OF DC DISCHARGES*

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A DC gas discharge is inherently an open system, far removed from thermodynamic equilibrium. Due to the nonlinear nature of the processes and the presence of near-electrode layers in such a system, many unstable states are manifested and self-organization of various dissipative structures occurs [1,2]. These processes are determined by some critical values of control parameters, both external and internal, depending on the properties of the medium. The development of instabilities, especially near critical currents, often qualitatively and quantitatively changes the structure of the discharge, leading to new combustion regimes. It is worth noting that the discharge of atmospheric pressure is characterized by a fairly rapid heating of the gas to significant temperatures at low currents. In this case, a glow discharge without proper cooling of the electrodes quickly contracted and passes into an arc.

A qualitative picture of the current-voltage characteristics of a low-pressure gas discharge for low pressure is given in many monographs on plasma physics, which describes the different modes of burning discharges and transitions into each other. However, its full qualitative projection on the behavior of discharges of atmospheric pressure is not obvious. At the same time, it is clear that it is impossible to model DC discharges in a wide range of discharge currents with a description of the nucleation and formation of various types of instabilities without considering the processes occurring at the boundary of the "gas-discharge plasma-electrode".

In connection with the foregoing, in the framework of a single extended hydrodynamic model, various modes of burning of direct current discharges were numerically studied in a wide range of discharge currents and various scenarios of transients and formation of current spots on electrodes were described.

In particular, results were obtained that demonstrate different scenarios for the transition from a normal TR to an arc: with a section on the I–V characteristic corresponding to the anomalous TR and without it. The variants are demonstrated in which round, annular as well as their combination current spots on the electrodes are realized in the normal mode of burning discharges. For the arc mode of discharge discharge, the results with diffusion and contracted current spots on the cathode are presented, depending on the cooling options.

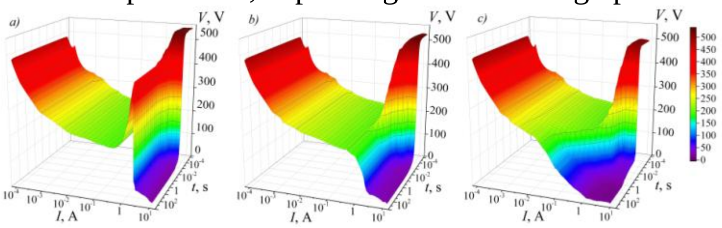

Fig.1. The evolution of the current-voltage characteristics of DC in the case of three different options for cooling the electrodes

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EFFECT OF SUPERSONIC GAS FLOW ON THE STRUCTURE OF THE GLOW DISCHARGE.*

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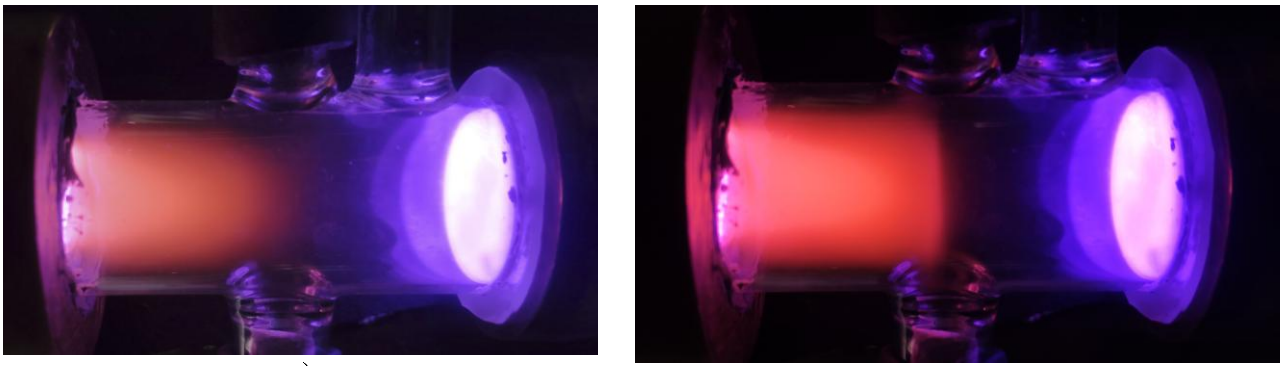
The development of methods and mechanisms for controlling the distribution of the characteristics of a gas-discharge plasma is relevant both from the point of view of studying the fundamental problems of plasma physics and from the point of view of numerous practical applications. In our recent work, the idea of changing the density of neutral particles in a gas-discharge gap by creating a supersonic gas flow was proposed. This, in turn, determines the localization of both the near-electrode zones and the positive column of a glow discharge.

In this paper, the methodological studies of these ideas are continued. For experimental studies, a discharge chamber of molybdenum glass of cylindrical geometry with water-cooled copper electrodes was performed. The interelectrode distance was 50 mm, and the diameter of the discharge tube was 30 mm. In a tube in a perpendicular to the direction of the axis of the tube, Laval micro-nozzles and a diffuser were placed. A diffuser through a vacuum hose was connected to the receiver. During the experiment, a vacuum was created in the receiver and a supersonic flow was made through the discharge zone. Figure 1 shows a photograph of the discharge during the experiment.



a) b)

Fig. 1. Glow discharge glowing at a pressure of 7 Torr: a) in the quiescent air; b) in the supersonic air flow. The cathode on the right, the anode on the left, the nozzle in the center below

As can be seen from Fig. 1, the supersonic flow strictly defines the zone of localization of the positive column. To the region of supersonic flow, we see Faraday dark space. In a fairly wide range of gas pressure and discharge currents, this localization is preserved.

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STUDY OF IONIZATION WAVES IN A PULSE DISCHARGE IN ARGON[1]

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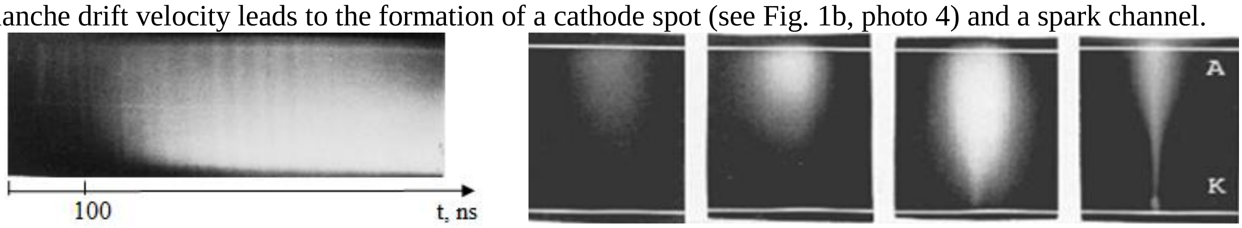
In this paper, an experimental and numerical study of the features of formation and development at the initial stages of breakdown of both the ionization fronts of the luminescence and the physical processes that cause the volumetric discharge instability in atmospheric pressure Ar is performed. The investigations were carried out in short intervals (d = 1 cm), with a discharge area s = 12 cm^2 at voltages in the range from a statistical breakdown (Ust = 6.8 kV at d = 1 cm, p = 1 atm) to hundreds of percent of overvoltages (up to 20 kV) in a preionized gaseous medium with electron concentration $n_0 \sim 10^7 cm^{-3}$. The experimental setup is similar to that described earlier in Refs.[1].

In the experiments, discharge diagnostics included the recording of voltage and discharge current on the discharge gap (respectively ohmic divider and low-inductance shunt) using digital oscilloscopes such as Aktakom and Tektronix, photographing the integral glow of the discharge, as well as photographing spatio-temporal patterns of glow of the gap using a photoelectric recorder (FER-2).

In Fig. 1 successive shots of the development of the discharge in argon, obtained during preionization, are shown. When the initial concentration of electrons is created in the interval $n_0 \cdot 10^7$ cm^{-3} and insignificant overvoltages, the first recorded luminescence appears at the anode by the instant of a sharp increase in current at an electron concentration ~ 10^{12}-10^{13} cm^{-3} and propagates to the cathode with a velocity ~ (2-5) · 10^7 cm/s. The speed is determined from the photos of the slit scan (see Fig. 1a).

As the emission front approaches the cathode, the electron concentration at the wave front increases and reaches values of 10^{13}-10^{14} cm^{-3}. At this stage, the discharge current has a value of 1-10 A. The overlapping of the discharge gap by an ionization front with a velocity an order of magnitude greater than the electron avalanche drift velocity leads to the formation of a cathode spot (see Fig. 1b, photo 4) and a spark channel.



a) b)

Fig.1. Space-time frames for the formation of a spark channel in argon with gas preionization in the gap (anode –in the top, cathode – in the bottom, d = 1 cm, p = 760 Torr, Ust = 10 kV)

A two-dimensional axisymmetric calculation of the development of ionization waves in argon at atmospheric pressure was performed. The discharge was ignited between two parallel plates with a radius of 2 cm and an interelectrode distance of 1 cm. The voltage on the electrodes was constant throughout the calculation and was 25 kV. The calculation model includes the particle balance equation for electrons, atomic and molecular ions, lower excited levels of Ar ($1s_5$), Ar ($1s_4$), Ar ($1s_3$), Ar ($1s_2$), highly excited levels of Ar (hl) (combining 2p, 2s , 3d, 3p in one level) and excimers. In total, more than 130 reactions were considered. The constants were taken from and determined by the electron temperature, which was found from the solution of the equation for the electron energy. The self-consistent electric field was found from the Poisson equation. The calculation was performed according to an explicit scheme with the second order of accuracy in time and space. The convergence of the solution was confirmed by the coincidence of the calculated values on different grids. In the interelectrode gap, the grid was uniform, along the radius - with thickening. The initial concentration was set on the axis of the discharge gap by a Gaussian function with a maximum concentration of electrons and atomic ions 10^7 cm^{-3}.

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OPTICAL AND KINETIC CHARACTERISTICS OF A PULSED DISCHARGE IN ARGON WITH ALUMINUM VAPOR AT ATMOSPHERIC PRESSURE[1]

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The study of the space-time dynamics of a pulsed discharge formation in atmospheric pressure argon in centimeter inter electrode gaps (with an initial electron concentration in the interval n_0 ~10^7cm^{-3} and insignificant over voltages *W*~ (10-100%) show that during the formation of a discharge, the first recorded luminescence occurs on anode, which propagates to the cathode at a velocity of ≈ 2-5·10^7 cm/s [1]. As the emission front moves toward the cathode, the electron concentration in it increases and reaches values of ~10^{13}-10^{14} cm^{-3}.

We have carried out investigations of the emission spectra from the near-cathode plasma of the discharge in atmospheric pressure argon. It has been established that with the formation of a cathode spot, the spectrum of the near-cathode plasma is characterized by intense lines of the cathode material *AlII* 396.1 nm, 394.4 nm, 280.1 nm, 281.6 nm with high excitation potentials and an intense continuum in the 260-360 nm range. The lines of aluminum ions are recorded simultaneously with the onset of a sharp current increase and reach a maximum value in 20-30 ns. After 30 ns from the onset of sharp current growth, the Stark half-width of the 480.6 nm argon line is 0.5-0.6 nm, and the line 422.8 nm ≈ 0.5 nm. These half-widths correspond to an electron density of ~ 10^{19} cm^{-3}, and after 20 ns the concentration decreases to a value of $2\cdot10^{18}$ cm^{-3}.

The effect of a longitudinal magnetic field on the emission spectra of a cathode plasma of a discharge is investigated. It is established that with an increase in the strength of the magnetic field the maximum radiation energy shifted to the short-wave region of the spectrum: at H = 0, λ_{max} = 420 nm, at H = 140 kOe - 400 nm, at H = 200 kOe - 380 nm. Thus, in the magnetic field the intensity of continuous radiation increases, the brightness of the ion lines in the ultraviolet region also increases: *ArII* 280.6 nm, *ArIV* 280.9 nm and lines of the electrode material *Al*-280.1 nm, 281.6 nm.

At the stage of slow channel expansion, i.e. from the moment t = 500 ns, the intensity of continuous radiation decreases, the intensity of ionic lines also decreases, while the brightness of the lines of neutral argon is 394.89 nm, 392.9 nm and aluminum lines *AlI* - 302.9 nm, 308.2 nm; *AlII* - 281.6 nm, 280.1 nm increases. In the longitudinal magnetic field, from the moment t = 700 ns, the emission of *ArI* lines 394.89 nm strongly increases; *ArII* 280.6 nm; *ArIV* 280.9 nm and aluminum 281.6 nm; 280.1 nm; 309.27 nm and 308.216 nm, while the intensity of the lines in the visible range of the spectrum decreases with increasing magnetic field strength.

In this paper, we consider the electron drift in argon with aluminum vapor in order to study the effect of the concentration (or fraction) of aluminum on the electron transfer coefficients. The computational experiment is based on the consideration of an ensemble of electrons that do not interact with each other, whose motion is determined by given fields and instantaneous collisions with atoms. The collision model is based on the random number generation procedure, i.e., the Monte Carlo method takes into account the energy balance of electrons based on elementary acts, including in inelastic collisions.

A model of collisions of ions with gas atoms, taking into account the resonant ion exchange, polarization and short-range (gas-kinetic) interaction, is constructed. On the basis of experimental data on ion mobility and the results of modeling collisions of ions with atoms of their own gas in a uniform electric field, the cross sections for resonant charge exchange of ions of noble gases, aluminum and copper were calculated. The influence of the electric field, the temperature of the buffer gas atoms and the percentage composition of the gas mixture on the ion velocity distribution function was investigated.

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STUDY OF IONIZATION WAVES IN A PULSE DISCHARGE IN HELIUM[1]

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The paper presents the results of experimental and numerical studies of the formation and development of an ionization wave in atmospheric pressure helium.

The experimental setup and research methods are given in [1]. The voltage across the gap varied in the range 3-20 kV. The voltage and discharge current were recorded, respectively, by an ohmic divider and a low-inductance shunt using digital oscilloscopes such as Aktakom and Tektronix. The space-time development of the discharge was filmed by a photoelectric recorder FER2-1. Preliminary ionization of the gas (n_0~10^8 cm^{-3}) was achieved by irradiating the gap through the grid anode with UV light from an external spark discharge. The 1 cm long test gap was formed by a mesh anode and a solid cathode 4 cm in diameter made of stainless steel.

Of greatest interest are the experimental results of direct observations of the dynamics of the formation of a discharge with spatial and temporal resolution in the nanosecond time range, obtained using FER2-1.

It was established experimentally that the first recorded luminescence occurs at the anode after the application of an external field, which then propagates as a diffuse luminescence to the cathode with a characteristic speed of ~ 10^7 cm /s. The glow front is not uniform, the intensity decreases from the discharge axis to the periphery, which indicates a higher intensity of ionization processes on the discharge axis. After the arrival of the luminescence front at the cathode, the discharge passes into the next phase, the phase burning phase.

At low breakdown voltages U0 <6 kV, a discharge is formed with a high emission uniformity and burning duration. At voltages U0> 6 kV and current densities $j \geq 40$ A/cm^2, plasma channels are attached to the cathode spots in the cathode region. With an increase in the number of cathode spots, the appearance of a spark channel in the gap is delayed, and many thread-like channels are formed. It has been established that with an increase in the energy input to the pre-ionization source, the uniformity and stability of the volume discharge increases. At very high overvoltages $U_0 \geq 12$ kV, the discharge is ignited in the high-current diffusion mode.

To describe the discharge, a two-dimensional axisymmetric diffusion-drift model of the motion of electrons and ions is used together with the Poisson equation.

It is shown that the formation of a discharge occurs during the development of a cathode-directed ionization wave, which is confirmed both by the results of numerical simulation and the results of experimental studies of the spatial-temporal dynamics of the development of the initial stages of the discharge. The transverse inhomogeneity of the gas pre-ionization forms an inhomogeneous ionization front wave developing from the central gap. The non-uniformity of pre-ionization of gas both along and across the discharge gap leads to non-uniformity of the electron concentration distribution across the discharge gap, therefore, the ionization wave front is not flat, but has an elongated shape. The rate of the ionization front decreases from the center of the discharge gap to the periphery.

As the cathode approaches, the field strength at the ionization front also increases, and the intensity of the ionization processes increases accordingly. With a decrease in the preionization electron concentration, the formation time of the ionization wave increases, respectively, and the discharge formation time.

The study of the kinetic processes of formation of a plasma column in gas He at a pressure of 1 atm in a non-uniform discharge based on a two-dimensional model has been performed. The initiation of 1-3 cathode spots, with a distance between them of 0.5 cm, was carried out by distorting the surface of the cathode at local points, which created an increased field strength in the region of the cathode. The calculated space-time distributions of the electron concentration and field are obtained. The development of a discharge with increasing electron concentration in the range 10^6–10^8 см$^{-3}$ is considered. The dependence of the width of the plasma column on the energy introduced into the discharge is revealed.

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STUDY OF THE TEMPERATURE INFLUENCE ON STRUCTURAL-PHASE CHANGES IN PORCELAIN CERAMICS PRODUCTION

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Insulating porcelain ceramics (PC) plays an important role in the wide transportation and safe use of electricity. Porcelain ceramics have not only high mechanical properties, but also high voltage properties [1-3]. At present, many high voltage insulators do not meet the requirements, resulting in frequent firefighting and safety precautions. In addition, electric current losses cause economic inefficiency. Solving this problem has become one of the main research areas of scientists in the last decade. In this regard, special attention is paid to study the complex internal microstructural-phase changes in porcelain ceramics, improvement of functional qualities. PC is a complex mixture consisting of silicon and aluminum oxides. The degree of relative percentage of oxides affects the properties of porcelain ceramics, which requires additional research. Therefore, the aim was to study the effect of temperature on the structural-phase changes in the production of porcelain ceramics.

As a result, porcelain ceramics was prepared based on the local raw materials of the Kyrgyz Republic. Main chemical composition is: kaolin 45%, porcelain stone 28%, clay 20% and feldspar 7% [4].

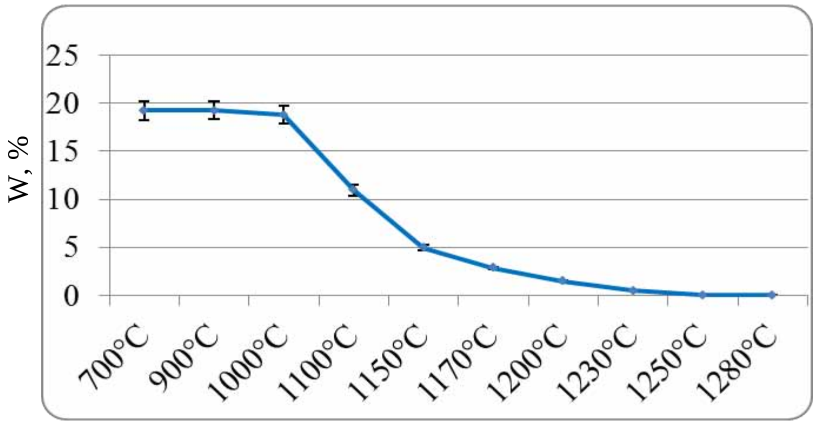

Fig. 1. Curve of change of the water absorption (W,%) of PC prototypes depending on their firing temperatures

Samples of ceramics was studied for water permeability at the temperatures of 700-900 °C. When the temperature reached 1280 °C water absorption decreased to 0.01%, and the volume decreased by 30%. This was due to the phase exchange, pore destruction, reduced size and weight, and the increase in density. PC obtained after the thermal treatment was studied using the X-ray pattern lines. It was found that it consisted of monoclinic and orthorhombic mesh. A new phase was observed on the X-ray spectra. Tensile strength of PC rose by 1.4% after heat treatment.

The effective mode of obtaining the porcelain ceramics was established along with the determination of regularities of structural-phase changes, the effect of temperature on the typical structure and mechanical properties and a harmonious combination of the vitreous phase with other phases.

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CHARACTERIZATION OF MAGNETRON PLASMA USING OPTICAL SPECTROSCOPY AND COLLISIONAL-RADIATIVE MODEL OF NITROGEN *

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Collision-radiative models (CRM) are widely used to determine the parameters of low-temperature plasma using optical spectroscopy [1]. Most of these models are global, i.e. describe the kinetics of spatially averaged quantities. In the case of discharges in nitrogen and nitrogen-containing gas mixtures, these models can be both relatively simple [2] and very complex, including hundreds of different reactions [3], depending on pressure, ionization degree and other conditions.

The magnetron discharge is characterized by low pressure and a relatively high ionization degree. In this case, the processes involving electron impact play the major role and some of the other processes may be neglected thus simplifying the model. On the other hand, the magnetron discharge has a spatial non-uniformity, which may question on the applicability of the global model.

In this work, we propose a method for determining plasma parameters of a magnetron discharge in nitrogen, based on global-local CRM and direct fit of synthetic emission spectrum to the experimental one. The global part of the model describes the kinetics of states with a longer lifetime, which can emerge in regions with a denser and hot plasma, and is transferred to the observation region. The local part of the model describes the states making the main contribution to radiation. The model takes into account the following processes: 1) excitation / quenching of N_2 states by electron impact; 2) excitation / quenching of metastable states by electron impact; 3) dissociation of N_2 due to electron impact; 4) optical transitions between the N_2 states; 5) vibration-vibrational and vibration-translational energy exchange processes for the ground $N_2(X)$ and metastable $N_2(A)$ states; 6) excitation of the N_2 states due to the collision of molecules in the metastable state $N_2(A)$; 7) quenching due to collisions with heavy particles; 8) quenching due to diffusion and collisions with the walls of the vacuum chamber; 9) sputtering of target atoms and compound molecules; 10) chemisorption of atoms and gas molecules on the walls of the chamber and the target of the magnetron; 11) recombination of gas atoms with chemisorbed atoms on the surface covered by the compound.

Using this technique, we investigated the plasma in a laboratory installation for reactive sputter deposition of titanium oxynitrides at several pressures and powers. The rise of the discharge power leads to the increase of rotational temperature determined by contours of the first positive (FPS), second positive (SPS) and first negative (FNS) emission band systems. The temperatures determined by FPS and SPS are noticeably higher than the temperature for FNS. This may be due to the large contribution of collisions of heavy particles to the formation of the corresponding excited states. With increasing pressure, the global and local concentrations decrease, as well as the global electron temperature. A similar dependence of electron temperature and density on pressure was also observed in [4] and may be associated with an increase in diffusion flux across the magnetic field. With increasing power, an increase in electron concentration and a drop in global temperature are observed. A similar result was obtained in [5] and our previous works. Such dependence can be related to the ohmic heating mode [6].

The results are generally consistent with our previous studies of the magnetron discharge in this setup, and with the results of other authors. In addition, we evaluated the degree of dissociation of nitrogen molecules in two ways: theoretical and experimental. These estimates are in good agreement, especially at high discharge power.

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MEASURING THE EXPANSION VELOCITY OF PLASMA FORMED DURING ELECTRICAL BREAKDOWN ALONG AN EXPLODING AL FOIL IN A MEDIUM OF DISORBATED GASES*

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This paper presents experimental results on measuring the plasma expansion velocity formed during electrical breakdown along an exploding Al foil. Electrical breakdown occurs in the environment of a mixture of gases desorbed from the surface of the foil when it is heated by the flowing current. Aluminum foil had the dimensions: length 20 mm, thickness 6 microns, width varying from 0.93 to 1.05 mm. Foil explosion was carried out by a sinusoidal current with a period of oscillation of 1780 ns. The current amplitude varied depending on the charging voltage (U_c = 10, 20, and 30 kV) of a 0.25 μF capacitor and was about 6.5, 14, and 22 kA, respectively.

The plasma expansion velocity was measured using three electric probes under the earth potential and located at the edges and in the middle of an exploding foil. The distance from the foil to the probes varied from 2 to 16 mm. In the experiments, the time of appearance of the signal on the probes was measured relative to the moment of breakdown along the foil. Measuring the time of flight of the plasma from the foil to the probes, and knowing the distance to the probes, the plasma expansion velocity was calculated.

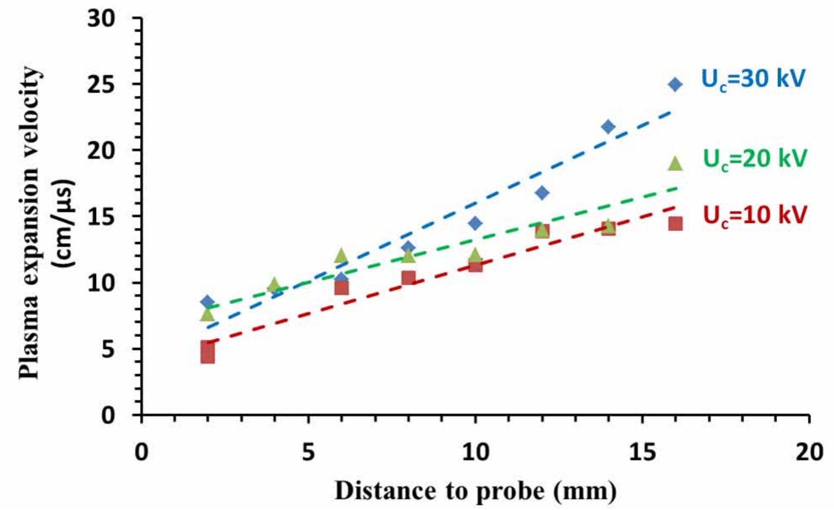

Fig. 1. The expansion velocity of plasma formed during the breakdown along the exploding aluminum foil at different capacitor charging voltages.

In addition to probe measurements, in this work, we recorded the optical images of an exploding foil and the glow of expanding plasma with four frame camera HFSC-Pro with an exposure time of 3 ns. These studies allowed us to get an idea of the shape of the forming plasma envelope and measure the rate of expansion of the bulk of the desorbed gases and metal vapors as a function of time. In addition, ideas were obtained about the processes occurring in the near-electrode regions at the moment of the occurrence of a breakdown.

* This work was supported by the Russian Foundation for Basic Research (grants No 17-08-00131). The authors are thankful to the Shared Research Facilities of the Tomsk Scientific Center of the Siberian Branch of the RAS for providing the HFSC-Pro camera.

THE MECHANODIFFUSION MODEL OF THE INITIAL STAGE OF PARTICLES FLOW INTRODUCTION PROCESS IN A TARGET SURFACE*

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The paper presents a coupled mathematical model of the initial stage of particles penetration in the metal surface in non-isothermal approximation. It is assumed that the implanted material there is sufficient energy to generate mechanical disturbances into target surface at the interaction moment. And mechanical disturbances effect on the redistribution of diffusion of implanted particles.

The simplified one-dimensional model includes the heat conduction equation (1), equation of implanted component balance (2) and the motion equation (3):

$$\rho C_\sigma \frac{\partial T}{\partial t} + \alpha_T T \frac{\partial \sigma}{\partial t} = -\frac{\partial \mathbf{J}_q}{\partial x} \tag{1}$$

$$\rho \frac{\partial C}{\partial t} = -\frac{\partial \mathbf{J}}{\partial x} \tag{2}$$

$$\rho \frac{\partial^2 u}{\partial t^2} = \frac{\partial \sigma}{\partial x} \tag{3}$$

The govering relations correspond to the theory of generalized thermoelastic diffusion:

$$\mathbf{J} = -\rho D \frac{\partial C}{\partial x} + BC \frac{\partial \sigma}{\partial x} - t_D \frac{\partial \mathbf{J}}{\partial t} \tag{4}$$

$$\mathbf{J}_q = -\lambda_T \frac{\partial T}{\partial x} - t_q \frac{\partial \mathbf{J}_q}{\partial t} \tag{5}$$

$$\sigma = E\left[\varepsilon - \alpha_T (T - T_0) - \Delta\alpha (C - C_0)\right] \tag{6}$$

The model takes into account the finiteness of relaxation times of heat and mass fluxes and the interaction of waves of different physical nature — impurity concentration, stresses (strain) and temperature. The problem was solved numerically with using the double sweep method. The Fig.1 presents examples of coupled problem solving for materials system - Mo(Ni).

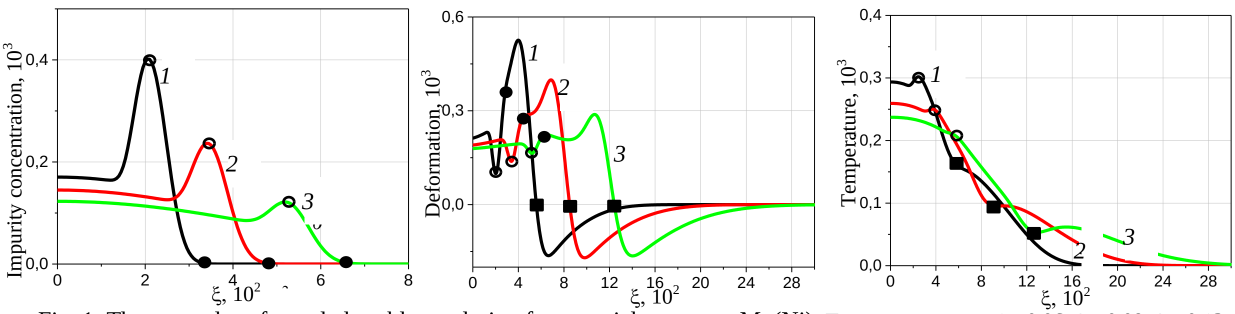

Fig. 1. The examples of coupled problem solution for materials system - Mo(Ni). Time moments, τ : *1* – 0,06, *2* – 0,09, *3* – 0,13

It is shown that the interaction of waves of different physical nature leads to the distribution of temperature and concentration do not correspond to the classical ideas (Fourier and Fick laws). The work demonstrated the distortions in the deformation and temperature waves which are the result of the interaction of the studied processes.

* This work was performed within the frame of the Fundamental Research Program of the State Academies of Sciences for 2013-2020, line of research III.23.

SIMULATION OF HIGH-PRESSURE GAS BREAKDOWN UNDER CONDITIONS OF SPATIALLY NON-UNIFORM INITIAL IONIZATION AND TEMPERATURE*

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The paper presents the results of numerical simulation of the extended atmospheric pressure discharge in configuration of the tip-to-plane diode (Fig.1.). The simulation is based on a modern hydrodynamic model of a discharge plasma in a pure O_2 medium at low average electric field strengths ~ 10 kV/cm. A voltage pulse with an amplitude of 100 kV with a duration of 2.5 μs and a leading front of 800 ns was applied to the electrodes with an interelectrode distance of 10 cm through the ballast resistance 10 kΩ. The following plasma chemical reactions for an electronegative gas were taken into account: ionization by electron impact with the formation of an O_2^+ ion, attachment of electrons with the formation of an O_2^- ion, direct dissociation of the molecule with the formation of atomic oxygen, and ion-ion recombination. It was investigated how different initial conditions (the presence of a weakly ionized plasma channel or a given temperature profile on the discharge axis) affect the initiation of a breakdown and the formation of a subsequent discharge structure (Fig. 2). The results of the calculations make it possible to qualitatively explain how the relaxing plasma generated by the previous pulse can influence the process of development of the discharge when the next voltage pulse is applied. These results will be used later to construct qualitative models of repetitively pulsed discharges with complex spatial geometry, for example, the apocampic discharge [1].

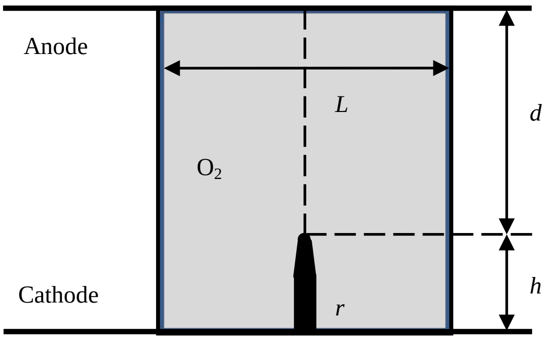

Fig. 1 – The computational domain configuration (h = 10 mm, L = 100 mm, d = 100 mm, r = 2 mm).

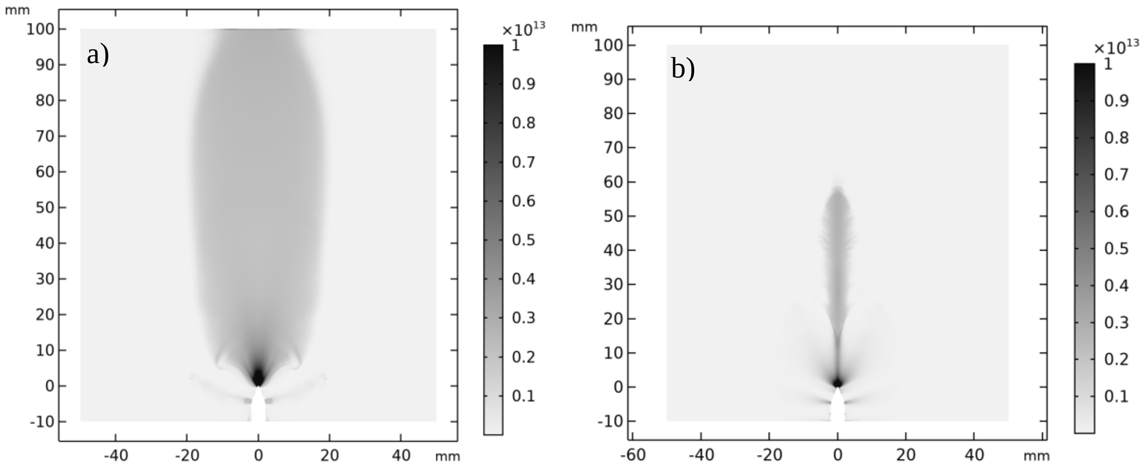

Fig. 2 – Spatial distribution of the O_2^+ number density (scale in cm^{-3}) for gas discharge a) without and b) with a Gaussian pre-ionization channel with an initial maximum concentration of positive ions of 10^{11} cm^{-3} in the center of the channel and a characteristic spatial parameter r_0 = 0.5 mm for the 400 ns time point.

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NEW METHOD OF CONDENSED SYSTEMS IGNITION BY LASER RADIATION*

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The dependence of the ignition delay time of high-energy materials (HEM) on the laser power is of practical importance in the design and calculation of HEM initiation systems (igniters, fuses, detonators), for evaluating the HEM explosion hazard under external thermal effects, and also used in determining the macrokinetics parameters of the ignition process by solving the inverse problem of chemical kinetics. In the experimental determination of the HEM ignition characteristics, optical furnaces or lasers with continuous or pulsed radiation are used [1, 2].

During HEM ignition by laser radiation, a significant factor is the uneven distribution of the density of the radiant heat flux over the surface of the irradiated HEMs sample. This is due to the presence of several types of transverse oscillations (modes) TEM_{mn} in an open laser resonator. The irregularity of the radiation flux density leads to the appearance of "hot" areas of uncontrollable dimensions on the HEMs sample surface, in which ignition is initiated. This leads to a large variation in results when measuring the ignition delay time.

This report presents a new method for determining the ignition characteristics of HEMs samples by laser radiation, which ensures the uniform distribution of the heat flux density over the surface of the sample during its ignition. The method consists of measuring the ignition delay time of a cylindrical HEMs sample when continuous laser radiation is applied to its end surface with a beam diameter equal to the sample diameter. The HEMs sample is pressed into a cylindrical tube. Before applying laser radiation, a rotational motion of the sample is created around its axis of symmetry with a constant angular velocity.

A theoretical estimate of the required angular velocity of sample rotation was performed, which averaged with a given error of the radiation flux density over the sample surface:

$$\omega \geq \left(\frac{q_0}{\Delta T_*}\right)^2 \frac{1}{2n\lambda\rho c} \ ,$$

where ω is angular velocity of the sample, rad/s; q_0 is average heat flux density of laser radiation, W/m^2; ΔT_* is the value of non-uniform heating of the sample surface, K; n is a number of radiation modes in the cross-section of the laser beam; λ is a thermal conductivity coefficient of the sample material, W/(m·K); ρ is a density of the sample material, kg/m^3; c is specific heat of the sample material, J/(kg·K).

The calculation of the heat flux density from the surface of the rotating sample into the environment was carried out according to the formula [3]:

$$q_S = \frac{\lambda}{R}\left(T_S - T\right) \cdot 0.329\sqrt{2\,\mathrm{Re}_\omega \,\mathrm{Pr}} \ ,$$

where q_s is heat flux density, W/m^2; R is disk radius, m; T_s is the surface temperature of the disk, K; T is ambient temperature, K; $\mathrm{Re}_\omega = \rho\omega R^2/\mu$ is rotational Reynolds number; μ is a coefficient of dynamic viscosity of the environment, Pa·s; $\mathrm{Pr} = \mu c_p/\lambda$ is Prandtl number; c_p is isobaric heat capacity of the environment, J/(kg·K).

The results of experiments on ignition HEM (pyroxylin) by CO_2-laser radiation with and without rotation of the sample are presented.

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AIR BREAKDOWN IN THE FIELD OF TRAVELING TEM-WAVE ASSISTED BY RUNAWAY ELECTRONS*

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An experiment was performed to study the breakdown of atmospheric air in the electric field of a traveling TEM-wave by dynamic reflectometry method. As a discharge gap, an air insulation gap of a 45-Ohm coaxial short-circuited line with a length of 40 cm was used. Breakdown localization was provided by replaceable inserts into the central electrode representing discs with a semi-toroidal edge and serving as electric field enhancer. The ledge with a height of 1.5 mm and 1 mm thickness, as well as a thinner 50-μm foil-made one, did not make significant inhomogeneities in the line with a radial clearance of 12.5 mm. Local impedance misalignments along the coaxial duct from subnanosecond RADAN generator (110 kV, 1 ns, 0.2 ns front) to the short-circuited line end did not exceed ±1 Ohm. The time of the double propagation of the wave between the insert and the short-circuited end of the line was 1.5 times longer than the pulse duration. This made it possible to use the method of dynamic reflectometry [1,2] and to obtain data on the dynamics of the breakdown in the electric field of a known magnitude and shape.

Reference mode when a gap in the region of the discharge is closed by the metal disk, gives the exact temporal reference of the investigated reflection. The principle is that when studying the development of the breakdown at the open end of the line it is very difficult to determine the real three-dimensional geometry of the electric field, part of the pulse energy is radiated into space and the front of the reflected pulse will be distorted. In the study of two-dimensional design load is only the dynamic resistance of the discharge that is in parallel with the wave impedance of the line, which gives the opportunity to analyze the rates of the voltage collapse, current rise, and discharge resistance.

When using a voltage pulse with an amplitude of –(80-110) kV, a 50-μm thin foil insert into the central electrode provided an electric field amplification sufficient not only to fulfill the field criterion for the thermal electrons runaway in the region of strong field distortion, but also to support the runaway mode of these accelerated particles in the rest of the radial gap [3]. Runaway electrons (RE) were recorded through a window in the outer line electrode by means of a collector sensor placed behind an aluminum foil filter or fine mesh. The voltage of -80 kV was the threshold for RE appearance. As the voltage amplitude increased, these particles were recorded from pulse to pulse without misses, which indicated a uniform emission along the enhancer circumference.

As a result, it was shown that the presence of RE leads to a multiple acceleration of the voltage collapse in comparison with the breakdown development without RE participation. The discharge resistance after 1 ns was noticeably lower (~10 and ~50 Ohms, respectively). The dependence of the discharge resistance on the RE current indicates their significant role in the pre-ionization of the gas. The collapse of the voltage began after the emission of RE and was further delayed at least for the time of their acceleration to the anode. Measurements with foil filters of different thickness showed that within accuracy of the registration the energy of the RE flow did not exceed the value determined by the voltage amplitude in the line. Thus, for 1 ns exposure at electric field strength of ~95 kV/cm, the noticeable delay of the pulse breakdown of atmospheric air is guaranteed. The obtained data demonstrate the possibilities of reflectometry for the study of fast processes in hard-to-investigate places.

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INVESTIGATION OF DEPENDENCE OF THE COMPOSITION OF CATHODE MATERIAL IONS IN LOW-CURRENT VACUUM ARCS ON THE CURRENT VALUE*

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The dependence of the average charge state of copper ions on the arc current value was investigated. The experiment was carried out in the range of discharge currents from 1.8 to 40 A. As opposed to the previous study [1], quasi-rectangle current pulses formed by a LC-line were used. Therefore the estimation of the actual current value was more accurate. Pulse duration was about 2 µs. The pulsed electrostatic gate was used to exclude from analysis the plasma flux formed at the ignition mode of the discharge. The charge composition of ions was obtained via the Thomson spectrometer with automated recording and processing of spectrograms.

The use of the electrostatic gate showed that the impact of the nonstationary processes corresponding to the gap breakdown stage is not significant. In Fig. 1. the diagram obtained with 4 µs gate located below the second one (without the gate), since the gate cut-off efficiency increases with the ion charge. However the trend lines of the dependences are almost parallel. The average charge variation with an increase in the arc current is determined by a remarkable difference between the growth rate of the quantity of Cu+ ions and the ions with the +2 charge and higher. The quantity of the multiply charged ions increases with the current considerably faster. And the arc current value, and therefore the quantity of emission centers, probably is an essential factor influencing the plasma charge state. Since the charge state of the cathode material ions depends on the quantity of simultaneously operating explosive emission centers, it can be supposed, that ionization processes take place in the plasma layer above the cathode spot and at least at the distances sufficiently larger than 1 µm. Probably it occurs due to plasma density increasing with the quantity of cathode spot cells, when an interaction between the plasma jets of different cells takes place. Concentration of hydrogen ions in the arc plasma can affect the ionization of cathode material ions, especially in the current range lower than 15 - 20 A in case of copper cathode. However probably it is not a predominant factor.

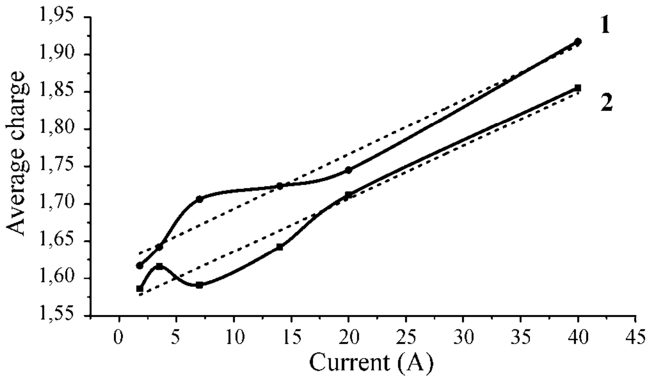

Fig. 1. Dependences of average charge of copper ions on discharge current with trendlines. 1 - Disabled gate; 2 - 4 µs gate pulse duration.

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DEPENDENCE OF THE PLASMA COMPOSITION IN THE LOW-CURRENT VACUUM ARC DISCHARGE WITH THE CUCR CATHODE ON THE CURRENT VALUE AND SURFACE CONDITIONS [*]

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At the moment there are investigations that show a corresponding of vacuum arc plasma composition to the elemental composition of the CuCr cathode material at the discharge current values about 500 A [1]. And also there are investigations of low-current vacuum arcs which demonstrate a tendency of cathode spots to appear mostly on the chromium grains when the grains are sufficiently large, and absence of the tendency when the grains size is in nanometer range [2, 3]. From this fact a hypothesis of the prevalence of the chromium ions in the low-current vacuum arc plasma on the CuCr cathode and the equivalence the fraction of chromium ions to the fraction of chromium in the cathode material at higher currents was derived. Dependence of the mass-charge composition of the ion flux from the plasma of the vacuum arc with the cathode made of CuCr on a value of the discharge current was investigated via the Thomson spectrometer with automatic signal registration and analysis. The microsecond arc was formed in a millimeter gap between CuCr cathode and copper anode under high vacuum conditions. The arc current was changed within the range from a few to tens of ampere. At the highest current range the plasma composition corresponded the elemental composition of the cathode surface. E.g. Fig.1. shows one of the experimental results. The sample used in the experiment has about 56% of chromium atoms and 44 % of copper atoms on the surface. This values corresponds the fractions of the ions of copper and chromium obtained at the arc current 75A. The surface analysis was made by means of the scanning electron microscope. The fraction of the chromium ions significantly decreased with the arc current decreasing below 30 A. There was noticeable increasing of the fraction of the chromium ions in the plasma at the discharge currents near the threshold values for the cathode materials. The effect appeared on coarse-grained non-melted cathode surfaces, and vanished after a multiple arcing. Therefore both of the effects described in [1-3] were confirmed. And the background of the effects was the increase of the copper ions fraction with the current decrease.

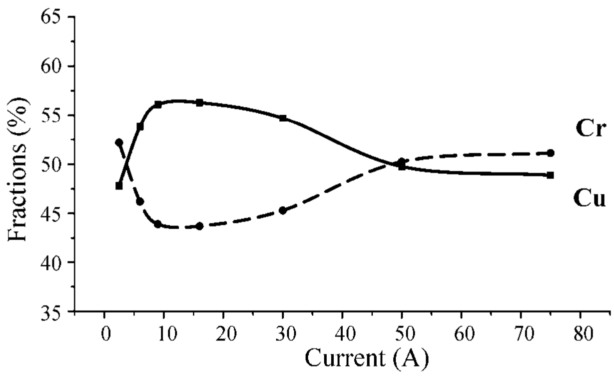

Fig. 1. Aggregated percentages of copper and chromium ions in the registered cathode material ion flow depending on the arc current value. Ascending current values.

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INVESTIGATION OF FEATURES OF CRATER FORMATION ON THE CATHODE SURFACE IN THE SHORT VACUUM DISCHARGE *

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The complex investigation (ion erosion, droplet erosion, crater formation) of a short (10-100ns) vacuum arc discharge has been carried out. The using of the short discharge time made it possible to examine in detail the evolution of cathode erosion. The cable generator with several pulse durations (8ns, 18ns, 45ns, 100ns) was used. The short vacuum discharge was burned on multi-pin tungsten cathode. The discharge was ignited by needle anode, which was moved over cathode surface. The discharge current, ion current was recorded and quantity of droplets was estimated for each discharge pulse. The dependence of averaged values of total ion charge and droplets amount on pulse duration was achieved. The erosion traces on cathode surface was analyzed. Three types of erosion traces can be distinguished: deep craters, rudimentary crater and melted erosion areas. The formation of the deep craters began at the durations exceeding 20ns. The form of these craters suggests that the current was constricted in a very small area which radius was less than 2mkm.

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DISTRIBUTION OF PLASMA POTENTIAL NEAR THE INFINITE CHAIN OF DUST PARTICLES *

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Solid micron-sized particles which are immersed in low-temperature plasma obtain a great charge (Zd = 10^3 -10^5e). Ions accumulate around such particles and an ion cloud is formed. Such systems had been already thoroughly investigated [1]. It can be confidently stated that the task of determination of the self-consistent distribution of ions and electrons around isolated dust particles is solved fully. With the solution of this problem, the following arises – how to numerically determine the self-consistent distribution of the potential around a cluster of dust particles.

Based on the modification of the code used in [2], the authors of this paper have considered at a qualitative level the distribution of a self-consistent potential around an infinite one-dimensional chain of dust particles oriented along the Z-axis. The potential in this system was determined by the following formula:

$$U(r,\theta) = -\frac{\tilde{Q}}{r} - \sum_k \frac{\tilde{Q}}{r_{k,2}} - \sum_k \frac{\tilde{Q}}{r_{k,1}} + \int \frac{n(r',\theta')d^3r}{|r-r'|} + \sum_k \int \frac{n(r',\theta')d^3r}{|r_{k,1}-r'|} + \sum_k \int \frac{n(r',\theta')d^3r}{|r_{k,2}-r'|}, \quad (1)$$

$$r_{k,1}{}^2 = (D^2 + r^2 - 2kdz), \quad r_{k,2}{}^2 = (D^2 + r^2 + 2kdz), \quad (2)$$

where $\tilde{Q}$ - dimensionless dust particle charge, D - interparticle distance.

Based on the data obtained, the dependence of the dust particle charge on the interparticle distance is presented, and a comparison with the case, where the dust particle is isolated, is made.

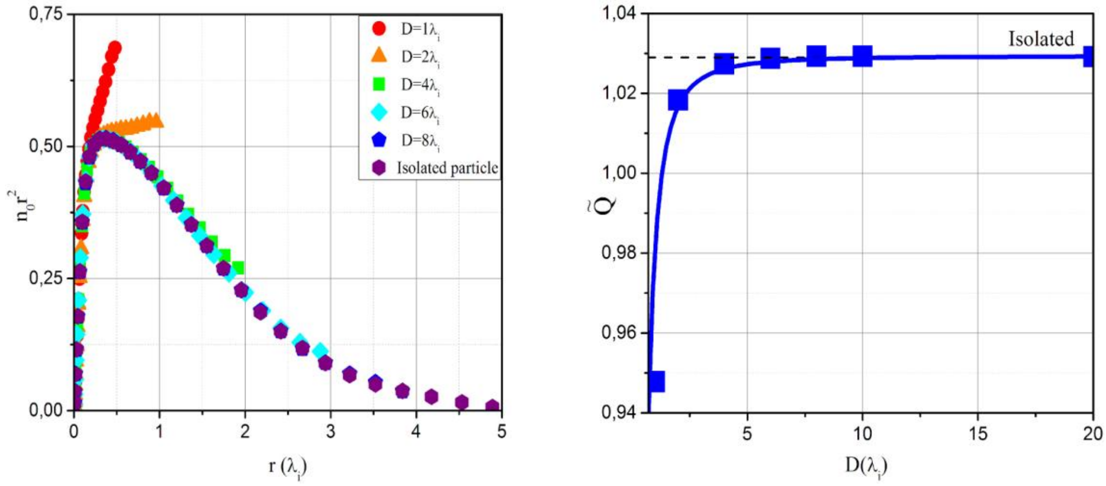

Fig. 1. The zero (isotropic) term $n_0(r)r^2$ of the expansion of the space charge density in the Legendre polynomials (left) and the charge of dust particles Q (D) (right) for different interparticle distances D.

From the analysis of the data obtained, it follows that the charge of each individual dust particle decreases, with the decrease of the interparticle distance, which is in a good agreement with the numerous experiments. A particle can be considered isolated at an interparticle distance greater than six Debye ion lengths.

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SPACE CHARGE SHEATH NEAR DIELECTRIC TARGET, IRRADIATED BY ELECTRON BEAM*

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Measuring the potential of a dielectric target irradiated by an electron beam can be considered as an independent task due to the many options in which it arises. It should be recognized that a single solution does not seem to exist. In this paper, we consider one of the options that is realized when a dielectric is irradiated by an electron beam with an energy of 2–10 keV and a current density of 1–10 mA/cm^2 in a forevacuum, i.e. in the pressure range of 1-100 Pa [1]. In this case, the electron beam forms a plasma column, clearly visible to the naked eye (Fig. 1). The plasma column is separated from the target by a dark gap representing the area of potential drop, i.e. space charge sheath. Experiments performed with a metal target showed that a change in the negative potential at the target affects the length of the sheath. This circumstance allowed us to associate the length of the sheath with the potential of the target and thus propose a method for determining the potential of the dielectric target. As shown by experiments conducted with an isolated metal, as well as with dielectric targets, the target potential is determined by a set of factors, of which the most important are the target material and the electron beam energy (Fig. 2). This indicates the connection of the target potential with the secondary emission properties of its material.

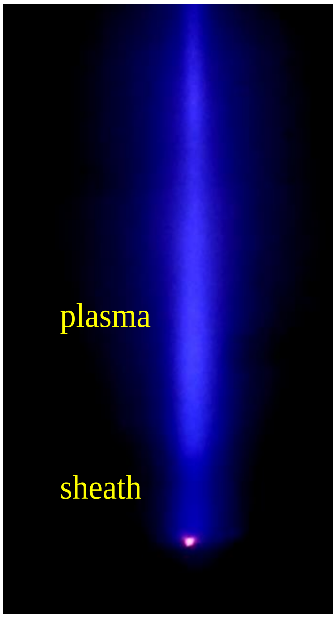

Fig. 1. View of beam and sheath.

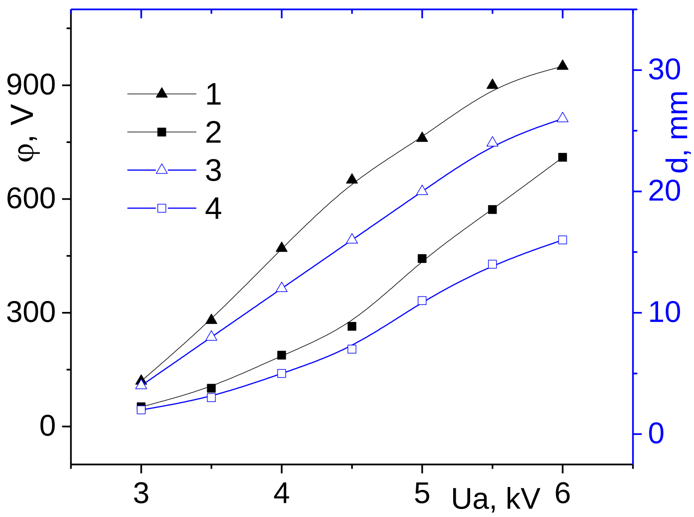

Fig. 2. The potential φ (1, 2) of the target and the thickness d (3, 4) of the layer as a function of the accelerating voltage Ua for isolated titanium (1, 3) and quartz (2, 4) targets.

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THE EMISSION SPECTRA OF GAS MIXTURES PLASMA INDUCED BY THE PRODUCTS OF ^{6}Li(n,α)^{3}H NUCLEAR REACTION*

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The main processes in the plasma created by reactor irradiation are similar to processes in a gas-discharge recombining plasma. The research of optical radiation of the nuclear-excited plasma induced by products of nuclear reactions is interest for development of an alternative outlet method of energy from the nuclear reactor, creation of ionizing radiation detectors as well as creation of one of diagnostics of high-temperature plasma in fusion reactors [1].

This work presents the results of the reactor experiments to study the spectral-luminescent characteristics of noble gases and their binary mixtures in a 200-975 nm spectral range, with excitation gaseous media by products of ^{6}Li(n,α)^{3}H nuclear reaction. The reactor experiments was held on the LIANA experimental bench, located in a stationary reactor hall, at a flux of thermal neutrons of $1.44 \cdot 10^{14}$ n/cm^{2}s.

Lithium layer (with enrichment by ^{6}Li – 7.5%) with a thickness of about 0.05 mm was applied to the inner surface of 12 mm diameter and 150 mm length tube. The tube with lithium layer was connected with the tube of 20 mm diameter and 600 mm length, sealed at the end by the flange with optical vacuum input. An output of light emission was implemented with the collimator with a quartz lens, inside the ampoule device (AD) and connected with the fiber-optic cable through the optical vacuum input. Light emission from the ampoule device got into the QE65Pro (Ocean Optics) spectrometer's input through the 10 m length fiber (P600-10-UV-VIS) and was recorded as a luminescence spectrum on the hard disk of PC.

Lines of 2p-1s-transitions of atoms (Paschen notations) prevail in spectra of clean noble gases. Strong molecular bands were observed in the binary mixtures of noble gases. Molecular bands observed in the emission spectra of paired mixtures of inert gases, were identified [2] as the transitions between states of heteronuclear ionic molecules. A powerful band in Kr-Xe mixture with maximum at 491 nm (figure 1) and the weaker band in Ar-Kr with maximum at 642 nm were observed in experiments. Not only transitions from $Ar^+(^2P_{1/2})Xe$ level at 329 and 506 nm, but also from Ar^+(2P3/2)Xe level at 346 and 545 nm, weak band at 349 nm were observed in Ar-Xe mixture. This result strikingly differs not only from the case of radioisotope pumping but also from the case of excitation by ion beam for the same degree of pumping power [3]. A possible explanation could be the quenching of Ar^+(2P1/2)Xe level to an underlying level in the presence of high xenon content, but during ion pumping transitions from $Ar^{+(}$2P3/2)Xe level are also absent in Ar(445 Torr)-Xe(50 Torr) mixture [3]. Band in the region 663 nm, which could correspond to the transition from Kr^+(2P3/2)Xe, was absent in Kr-Xe mixture.

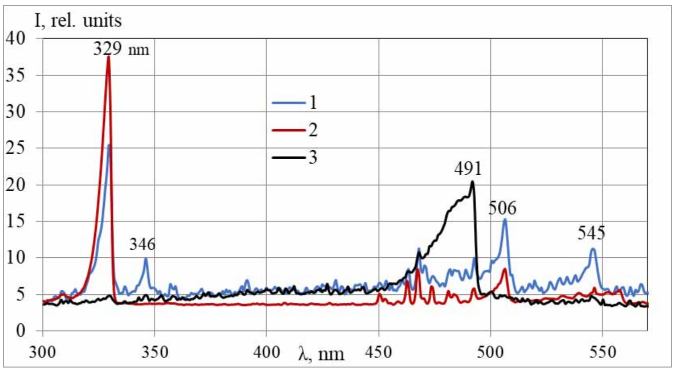

Fig. 1: Luminescence spectra of mixtures of Ar(690 Torr)-Xe(68 Torr) (1), Ar(600 Torr)-Xe(6 Torr) (2) and Kr(380 Torr)-Xe(380 Torr) (3) under excitation at the nuclear reactor (1,3) and by beam of argon with 70 MeV energy (2).

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THE FORMATION OF TUNGSTEN CARBIDES IN BEAM-PLASMA DISCHARGE OF CH_4 ON THE TUNGSTEN SURFACE

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At present, tungsten is supposed to be used as the divertor of a thermonuclear reactor facing the plasma, and beryllium and carbon-containing materials can be used as the first wall material [1].

Since beryllium will be used as the first wall, when a helium, formed as a result of a thermonuclear reaction, is exposed to it, the reaction takes place:

$$^{9}Be + {}^{4}He \rightarrow {}^{12}C + n, \tag{1}$$

Due to the processes of physical and chemical sputtering of carbon materials, the plasma will be contaminated with carbon and hydrocarbon impurities. In plasma, these impurities will be ionized by energy electrons and, then, together with hydrogen isotopes, implanted into tungsten. In this case, depending on the conditions of the plasma action, both carbon films and carbides may form on the surface of the tungsten divertor.

The presence of carbon accumulated in this way highlights the carbidization process of tungsten in a separate area of research. To date, studies on the formation of carbon films and tungsten carbides have been carried out by obtaining thin films of carbon and carbides (W_2C, WC) using various methods, such as magnetron sputtering [2], in plasma arc discharge [3], irradiation of tungsten with a stream of hydrogen plasma with the addition of carbon [4], chemical precipitation of carbon from the gas phase [5], or evaporation of carbon [6].

The appearance of carbon in the chamber of the thermonuclear reactor entails a number of problems [4]. By acting on the surface of the divertor in a mixture with hydrogen plasma, carbon can penetrate into the volume of the divertor and along with hydrogen ions contribute to erosion and the formation of porous layers on the surface of tungsten, as well as under certain conditions, the formation of carbides (W_2C, WC). Japanese scientists conducted research on this problem [4]. They studied the behavior of carbon on the surface of tungsten when the sample was irradiated with a deuterium ion beam with different carbon contents and changes in the beam parameters (energy, fluence) and sample temperature.

All experimental work on the deposition of a carbon coating in a plasma discharge of methane was carried out on a simulation bench with a beam plasma installation.

For the development of methods for coating the surface of tungsten, two programs have been developed. This is a program of experiments, which determined the conditions, processes and modes of operation of PBI under which the coating occurs. The second program defines methods for materials science studies, which include sample preparation, sample annealing, SEM, EDS, and X-ray phase analysis.

As a result, experiments were carried out in which samples of the brand SVI-1 (analog WY-20) were irradiated in the mode of a beam-plasma discharge in methane medium, at various values of the ion energy and the surface temperature of the sample.

As a result of materials research, the presence of a network of microcracks, erosion on the surface of tungsten samples was found, and the carbon content in the surface layer of the samples was determined in the range from 6 to 10% mass. X-ray phase analysis revealed the presence of carbide (WC) and half-carbide (W2C) tungsten peaks on samples W-12 and W-13.

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ELECTRIC ARC PLASMATORCH OF A TWO-CHAMBER SCHEME WITH REVERSE POLARITY OF ELECTRODES CONNECTION*

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The current density in the cathode region of an electric arc in an environment of molecular oxygen-containing gases is about 10^4 A / cm^2, and volts is the equivalent of heat flux into the cathode $U_E \approx 10$ V [1]. Thus, the heat flux density in the cathode reaches 10^5 W / cm^2. No method of cooling the electrode, except for thermal emission, is unable to divert this level of heat flux density without destroying it. Due to the presence of oxygen in the plasma gas, it is impossible to use tungsten thermocathodes, and thermochemical cathodes made of zirconium or hafnium that can work in an oxygen-containing atmosphere have an operating current of up to 300 A and a limited lifetime of continuous operation. Therefore, a common way to ensure the efficiency of the cathode in the environment of oxygen-containing gas is the dispersion of heat flux over its working surface by gas or magnetic scanning of the cathode portion of the electric arc column. In this case, copper is most widely used as an electrode material due to high heat and electrical conductivity. In this case, the typical level of specific erosion of the cathode in an air atmosphere is $\langle G \rangle = 1.5\ 10^{-9}$ kg/C.

Studies of cathode erosion in an environment of an oxygen-containing gas — air were carried out in a two-chamber plasma torch. Earlier studies [1] of erosion of a copper cathode in a two-chamber plasma torch with direct polarity for switching on the electrodes showed that the level of specific erosion has the usual value for air $\langle G \rangle = 1.5 \cdot 10^{-9}$ kg / C.

Data on work with reverse polarity of connection are absent, therefore, experiments were conducted in a two-chamber plasmatorch with reverse polarity of switching on the electrodes and self-adjusting arc length. The scheme of the plasma torch is shown in Fig. 1.

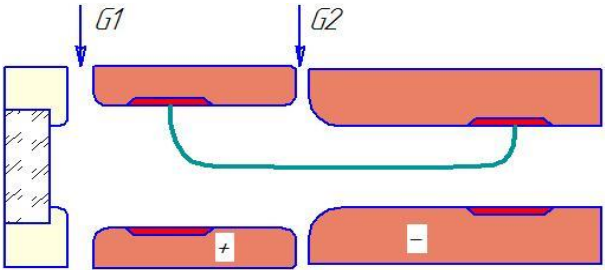

Fig. 1. Scheme of a two-chamber arc plasma torch with the connection with reverse polarity

The diameter of the channel of the internal electrode of the plasma torch - anode was 30 mm, and the diameter of the channel of the output electrode of the plasma torch - cathode was 20 mm. Air consumption through the swirlers is 20g / s, the operating current is 240 A. According to the results of more than 20 hours of experiments, it was found that there is no progressive increase in the thickness of copper oxides in the cathode arc channel characteristic of the output electrode — the anode with a direct polarity of the two-chamber plasma torch.

When the polarity of the switching of the plasmatorch electrodes was reversed, the voltage level was 660 V, which is 30% higher than the voltage level when the electrodes were turned on directly. Thus, the reverse polarity of the connection of a two-chamber plasmatorch with equal power provides a more than twofold increase in the service life of the plasma torch in comparison with the direct polarity of its connection. The level of specific erosion of the cathode was $\langle G \rangle = 8 \cdot 10^{-10}$ kg / C, which is two times less than the typical level of erosion of the cathode in an air atmosphere.

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NUMERICAL INVESTIGATION OF THE SURFACE BARRIER DISCHARGE IN THE AIR*

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The dielectric barrier discharge, as is known, has two forms of development: volume and surface. In a volume discharge, the gas layer in which the discharge develops is located between the dielectric-coated electrodes. In the surface discharge, when two electrodes of different widths are separated by a dielectric, it lies directly on the surface of the dielectric. The smaller electrode, to which a voltage is applied, and at the edge of which a discharge develops, will be called a high-voltage or working electrode. The potential of the opposite will be considered zero.

An intensive study of the surface barrier discharge began only a few years ago due to its promising use for controlling the laminar-turbulent transition and the position of air flow separation zones near solid surfaces by changing the parameters of the boundary layer.

In recent years, various models and numerical experiments based on them have appeared, which allow predicting the parameters of a surface barrier discharge depending on external conditions. It should also be noted that researchers are looking for ways to control the parameters of barrier discharges, including in the case of surface organization [1-2]. Accordingly, existing models and their numerical implementations are being developed.

In this regard, the aim of the presented work was to simulate the simplest version of the implementation of the surface barrier discharge in air at atmospheric pressure in the case of positive polarity applied voltage. Air is a multi-component molecular gas characterized by a vast set of elementary processes occurring on varied spatial and time scales. This is why the choice of a plasma-chemical model depends on the formulation of the problem.

In this work, air was considered as a mixture of nitrogen and oxygen (77% N_2, 23% O_2). Here, we applied a set of plasma-chemical reactions developed in other work [3], which considered only positive and negative molecular ions O_2^+ and O_2^- of air and six reactions containing these ions (table 1).

To perform a numerical simulation a fluid model of electrical discharge was formulated [1]. It is based on density balance equations for electrons, positive and negative ions, electrons heat balance equation, which takes into account not only the volume processes, but also the spatial transfer by conduction and the Poisson equation for finding a self-consistent electric potential. The mobility and diffusion coefficients for electrons, as well as some constants of the inelastic processes involving them, are calculated by convolving the electron distribution function, with the cross section. In this work the electron distribution function is assumed Maxwellian.

Preliminary numerical calculations have been carried out, demonstrating the formation of a streamer structure of the discharge in the case of the application of a positive potential to the working electrode. The dynamics of electron density and electric potential for a streamer form of discharge is presented.

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THE INTERRELATION BETWEEN OF THE GEOMETRY OF THE CHANNEL OF THE FLARE DISCHARGE AND ENERGY CHARACTERISTICS

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A high frequency flare discharge burning at atmospheric pressure is a plasma channel which surrounded by faint diffusion shell. The flow of high frequency current and the main energy release occurs in the zone of the discharge channel. Therefore, the physical characteristics of the flare discharge are determined by the size and shape of its channel.

The most important characteristic of the discharge is a thermal power. However, to date measurements of the thermal power of the discharge have been carried out, as a rule, without specifying the length of its channel. . In addition, the measurements were limited to the study of discharges with a power not exceeding 200 ... 300 watts. We also note that the lack of reliable experimental data on the relationship between the length of the discharge channel and its thermal power makes it difficult to verify existing theoretical models [1] of the discharge.

This paper presents the results of measuring the thermal power of a flare discharge burning in air , argon, and helium at atmospheric pressure, depending on the length of its channel. The thermal power was determined by summing the heat losses at the discharge electrode, the heat losses in the discharge chamber, and the heat flow of the discharge plasma in the axial direction.
The measurement results for a flare discharge burning in air are presented in Figure 1. As can be seen from the figure, the dependence of the discharge thermal power on the length of its channel is linear.

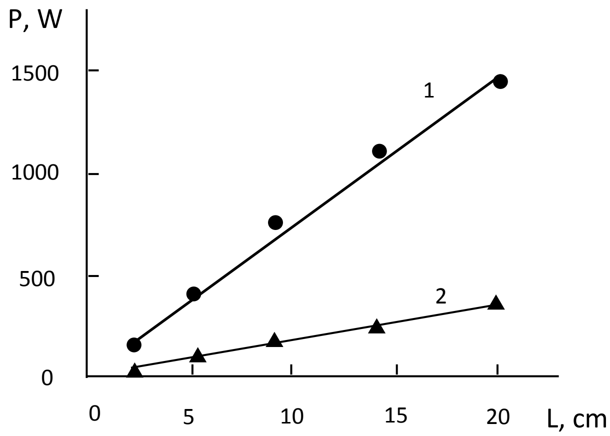

Fig . 1. The dependence of the thermal power of the flare discharge burning in the air from the length of his channel. 1 - total heat power ; 2 - heat losses on the electrode .

The dependence of the heat loss at the electrode on the length of the discharge channel has a similar character. Note that in the case of a flare discharge burning in air, the heat loss at the electrode is 12 ... 15% of the total discharge power. At the same time, for a flare discharge burning in helium, this value is 7 ... 8%. This difference is apparently due to the small value of the gas temperature of the helium plasma.

From the results of the measurements, it also follows that the discharge power is proportional to the cross-sectional area of its channel. Therefore, the diameter of the flare discharge channel is proportional to the square root of its thermal power. Note that this dependence is confirmed by the results of experimental measurements by other authors.

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PHENOMENA AT THE ELECTRODE SURFACES AND LOCALIZATION OF VOLUME DISCHARGES IN SMALL–SIZED SEALED–OFF TEA–CO_2 LASERS

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1. Introduction

Creation of sealed–off TEA–CO_2 lasers with a long time of working is directly connected with remaining of spatial homogeneity of a volume discharge, in plasma of which pumping is effected. Under the influence of the volume discharge in the laser mixture a large number of secondary compositions are accumulated. These compositions initiate a regeneration of the volume discharge into local one and limiting a lifetime of small–sized TEA–CO_2 lasers at a level of $10^3 \div 10^4$ pulses [1].

Regeneration of active mixtures with the help of catalysts enable to rise a lifetime up to $(1 \div 6)_* 10^6$ pulses. A localization of the volume discharge after $(1 \div 6)_* 10^6$ pulses is present in conditions of a very low CO_2 dissociation and low O_2 concentration and some other secondary compounds correspondingly.

These facts show that a localization of the volume discharge is defined not only by the ionization processes in a gas medium but also by the processes at the electrode surfaces. The present work is devoted to investigation of interrelations between a microstructure of electrode active surfaces with their autoemissive characteristics, a spatial structure of the volume discharge plasma and the resource of the small–sized sealed–off pulse–periodical TEA–CO_2 lasers.

2. Experimental investigations

All investigation works have been done with a TEA–CO_2 laser container with 10 independent gaps used to ignite a volume discharge. Al, Mg, stainless–steel, Ni, Cu, Mo, Ti, Ta, Nb and W are used as electrode materials. A volume discharge of nanosecond duration and an energy density W =150÷250 $mJ_* cm^{-3}$ was excited simultaneously in all gaps with a pulse repetition rate F =40 Hz. A condition of the electrode active surfaces before the influence of plasma of the volume discharge on them and after a definite number of current pulses of the volume discharge was controlled by an optical microscope Carl Zeiss (m≤500) or a raster electronic microscope JOEL–7 (m≤5000).

Autoelectronic currents were measured in a separate chamber ($P \leq 10^{-7}$ mm Hg). In the same chamber an electronic work function from electrode active surfaces was defined by a method of a “vibrating condenser” according to a contact potential difference. This value made it possible to define a coefficient of amplification of the electrical field and an area of emissive centers on the basis of the Fowler–Nordheim equation [2–4].

The values of the coefficient β increase in the same materials, where the most noticeable changes in the surface microstructure are observed. So, influence of plasma of the volume discharge on the electrode surface results in change in the surface microstructure and increase in local electrical fields. If the autoelectronic current gains values at which a thermal destruction of the autoemitter happens then in this point a local channel begins to form.

Increase in geometrical dimensions of microinhomogeneities at the electrode surfaces results in autoelectronic currents from these zones of the surfaces and initiates a formation the emission centers at them as a result of a transfer from the autoelectronic emission to an explosive one [3, 4].

The results pointed show to a definite role of the autoelectronic phenomena in destruction of the spatial homogeneity in plasma of the volume discharge. The same results indicate to a necessity of making electrodes of materials, which more stable to the influence of plasma of the volume discharge.

The resource of the TEA–CO_2 laser with electrodes of Al is 2.5 hours or $2_* 10^5$ pulses. When the electrodes made of nickel were used the resource is 56 hours. It is significantly exceeds 10^6 pulses. The largest resource is gained in the laser with electr5odes made of Ta. In this laser the resource is 110 hours which significantly exceeds 10^7 pulses.

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HIGH–VOLTAGE PULSE GENERATORS FOR EFFECTIVE PUMPING OF SUPER–ATMOSPHERIC PRESSURE CO_2–LASERS

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Effective excitation of super–atmospheric pressure volume discharges, pumping of CO_2–lasers at super–atmospheric pressures and effective generation of "runaway electrons" can be realized by using of very high voltage pulses with nanosecond rise times [1, 2].

The present work is devoted to describing construction of some types compact pulse generators with amplitude of voltage pulses up to 200 kV, rise–times about 10 nanoseconds and pulse energy per pulse up to 20 J.

The electrical scheme one of that pulse generators images in Fig.1. There are used two identical pulse transformers (PT_1, PT_2) and one high–current pseudo–spark switch (S) (TPI1–10k/50) (maximum voltage 50 kV, maximum pulse current 50 kA). Primary circuits of both transformers were connected in parallel. Secondary circuits were connected sequentially. Transformation coefficients of each transformer were n = 10. The capacitance values of main condensers C_0 were in range 0.025–0.1 μF. Initial charging voltage that condensers can vary in range U_O = 10–30 kV. Secondary condensers C_2 (400–1200 pF) can charges from two pulse transformers up to 200 kV with rise–time about 1.5÷2 μs. We used very quick switching spark gap (P) (gas pressure in spark gap equal 100 Atm.) for minimal shortening of rise–time of high voltage pulses. The own time of switch–on this spark switch was less than 1 nanosecond. Condenser C_2 with capacitance 50–200 pF can charges more than 220 kV. Voltage divider (D) and measurement transformer (MT) (they were constructed by recommendation in [3, 4]) ensure control of electrical parameters of volume discharge between the main electrodes A–C.

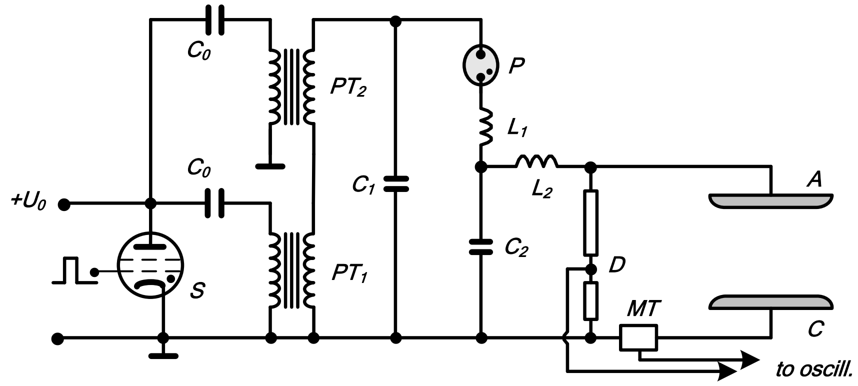

Fig.1. Electrical scheme of high–voltage generator with two pulse transformers

The main results of our work are the next:

– realized a new variant of small–sized pulse generator on the base of two pulse transformers and high–pressure peaking spark switch with maximal amplitude of pulse voltage up to 200 kV and with rise–time about 10 nanoseconds;

– fulfilled preliminary experiments with volume discharge forming in CO_2–laser mixtures at super–atmospheric pressures.

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METHODICS FOR ELECTRICAL DIAGNOSTIC OF THE PLASMA JET FORMED IN THE LOW-CURRENT PLASMATRON*

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Currently, plasma jets based on the atmospheric-pressure discharges are attracting increasable attention [1–3]. Frequently, the gas-discharge system for obtaining a plasma jet using the discharge in a gas flow are called a plasmatron. The electrodes of plasmatron are configured to allowing the gas to flow through the discharge region [1–4]. Thus, the heated flow of weakly ionized gas, so-called “plasma jet”, forms in the plasmatron nozzle [1–4].

This paper deals with the investigations of the plasma jet generated by using the atmospheric-pressure glow discharge in a vortex airflow with the electrode configuration corresponding to coaxial plasmatron. The discharge is supplied from the high-voltage DC voltage source. The ballast resistor is used for limiting discharge current at level less than 0.2 A. The air mass flow rate is varied from 0.1 g/s up to 0.3 gm/s. In these conditions, the mainly part of a total discharge current in plasmatron flows via the constricted positive column of the glow discharge and only a small fraction of electrical current is flowing through the jet volume.

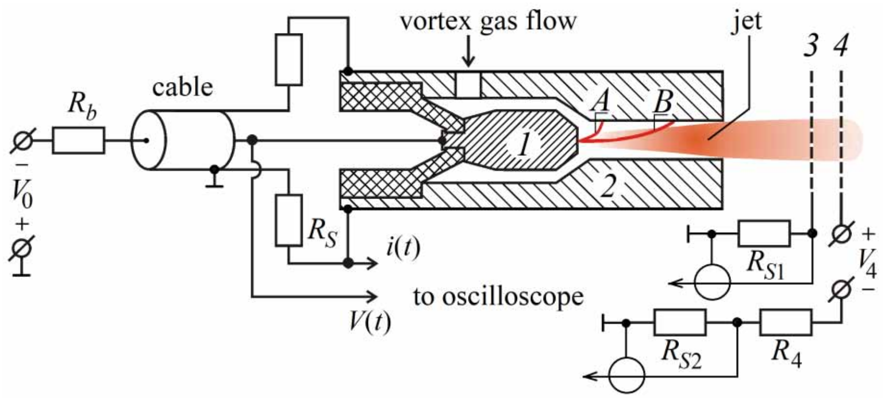

Fig. 1. Circuit of the experimental arrangement for diagnostic of the plasma jet. The discharge is sustained between the cathode of plasmatron 1 and the grounded anode 2 (a length of the plasmatron nozzle l = 20 mm, an inner diameter of the nozzle D = 5 mm). The system of additional diagnostically electrodes *3* and *4* are used to collect the currents flows through the jet volume. A, B – the positions of positive column (schematically). A typical DC voltage V_0 = (3 – 5) kV, $V_4 \leq 3$ kV, R_b = (20 – 42) kΩ, R_4 = 100 kΩ. The discharge burning voltage $V(t)$ is measured by the TDS-1012B oscilloscope with the high-voltage probe. The low-inductance shunts R_S = 1 Ω, R_{S1} = 1 kΩ and R_{S2} = 10 kΩ are used for the current signals measurement.

In the experiments the currents in the system of diagnostic electrodes is measured. The obtained data allow to concluding that the electrical current flowing through the jet volume forms due to electrons that can drifted from the discharge plasma region. It shown that the jet current magnitude is determined by the gas flow rate, by the discharge channel position and by the characteristics of the discharge in the plasmatron. The methodic for estimate the electron density in the jet volume has been proposed. Based on experimental data, the estimated value of the electron density in the jet is not less 10^9 cm^{-3}. At such value of electron density, the electric field distortion by the space charge of electrons can lead to the current self-limitation through the jet.

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THE EFFECT OF POLARITY ON THE FORMATION OF STREAMERS IN AN INHOMOGENEOUS ELECTRIC FIELD*

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It is well known that the polarity of voltage pulses affects the formation dynamics and parameters of a streamer. The effect of polarity is especially pronounced in the gaps with asymmetric distribution of the electric field strength. Breakdown voltage at positive polarity is less than at negative one (polarity effect) in conditions of slowly varying electric fields [1]. A negative electrode is the shielded by a cloud of immobile positive ions. As a result, higher electric field is required for the development of a negative streamer. Furthermore, with low overvoltage, a positive streamer develops faster than the negative one. In nanosecond discharges with high overvoltage levels, the inversion of polarity effect is observed: breakdown voltage at positive polarity becomes higher than at negative one [2–4]. In recent paper it was shown that at subnanosecond breakdown of a 1-cm tube-to-plane gap, the positive streamer appears later than the negative one [5]. As a result, the voltage at positive polarity increases to large values. However, the effect of polarity on a streamer velocity has not been studied in [5].

This paper presents the results of experimental studies of the effect of polarity on the streamer velocity at various voltage amplitudes. In the experiments, nanosecond voltage pulses were applied across an 8.5 mm point-to-plane gap filled with air and nitrogen at a pressure of 100 kPa. The formation of positive and negative streamers has been experimentally studied using a HSFC-PRO four-channel ICCD camera. Waveforms of voltage and discharge current pulses were also recorded. The propagation velocity of streamers was estimated by a dynamic displacement current (DDC) [6]. It was found that the negative streamer crosses the gap faster than the positive one (Fig. 1). This may be due to the features of the streamer shape near the pointed electrode, as well as the mechanism of gas pre-ionization before the streamer front.

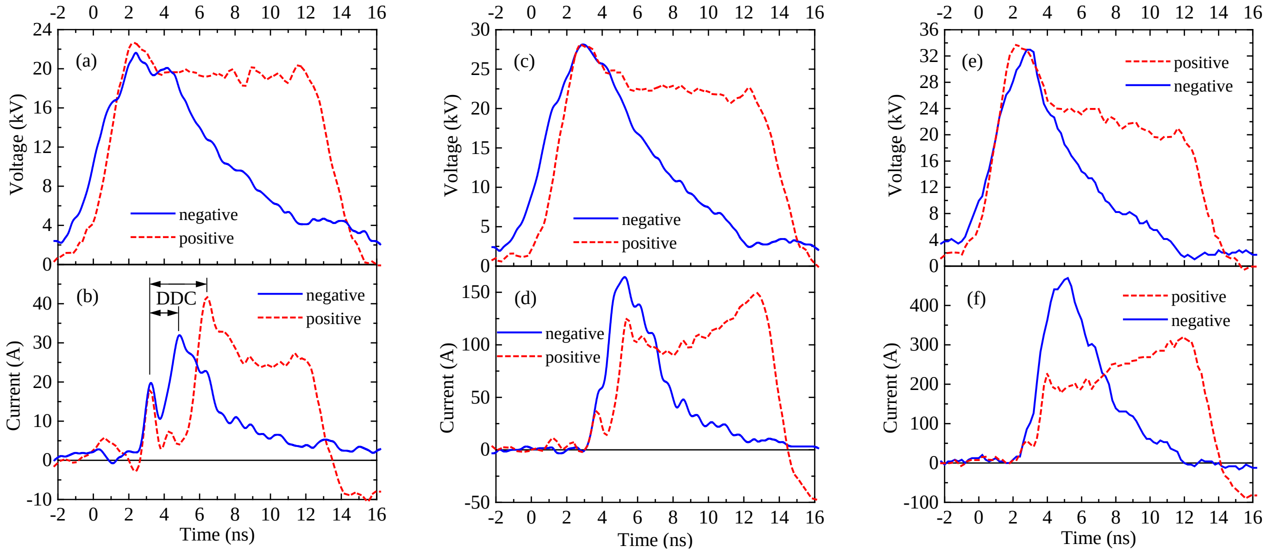

Fig. 1. Waveforms of (a, c, e) voltage and (b, d, f) current during discharge in atmospheric pressure air at different voltage amplitudes and polarities.

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ON THE INFLUENCE OF A CATHODE SHAPE ON THE PARAMETERS OF CURRENT PULSES OF RUNAWAY ELECTRON BEAMS AT APPLYING VOLTAGE PULSES WITH A RISE TIME OF 200 NS*

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Runaway electron beams generated during the breakdown of gaps with a cathode having a small radius of curvature are currently obtained in various gases at pressures from hundreds of Pa to thousands of kPa. Their parameters were measured in different conditions with a high temporal resolution [1]. However, such measurements were carried out under conditions of high overvoltages when applying voltage pulses with a subnanosecond and nanosecond front duration. In practical applications, voltage pulses with a rise time of 10^{-7}–10^{-6} s are widely used [2]. There are very few data on direct measurements of the parameters of runaway electron beams under these conditions. Noteworthy is the work [3] of 2018, in which studies were carried out with the rise time of ≈ 500 ns.

The purpose of this work is to study the influence of the cathode design on amplitude-time parameters of runaway electron beams at applying voltage pulses with the rise time of 200 ns.

The experimental studies were carried out on setup that allows measuring subnanosecond runaway electron beam current pulses with temporal resolution up to 100 ps. A GIN-35NP homemade voltage pulse generator was used. Different cathodes were used. The first one was made of a needle with a length of 5 mm, a base diameter of 1 mm, and a rounding radius of its tip of 75 µm. The second was tube with a diameter of 6 mm and a wall thickness of 100 µm. The third was made of a ball with a diameter of 14 mm. The grounded electrode was a plane. The gap width was 8.5 mm. The generator produces negative voltage pulses with an amplitude of up to 35 kV, the rise time of 200 ns, and a pulse duration $\tau_{0.5} \approx 270$ ns. To measure the parameters of a supershort avalanches electron beam (SAEB) [1], the grounded plane electrode was made of a grid. The SAEB current was measured with a 20-mm collector placed behind the grounded electrode. The grid had the mesh size of 400×400 µm and a transparency of 62%. In some experiments, a 2-µm kimfol ($C_{16}H_{14}O_3$) film coated with a 0.2 µm-thickness aluminum layer, as well as a 10-µm Al foil were used as the grounded electrode. The kimfol passes electrons with an energy of 10 keV and higher. The Al foil passes electrons with an energy above ≈40 keV. They were used as filters. The electrical signals from a capacitive voltage divider and the collector were recorded with a Keysight Tech MSOS804A digital oscilloscope (8 GHz, 20 GS/s). The bandwidths of a current shunt made of chip resistors and the 20-mm collector were no higher than 4–5 and 6 GHz, respectively.

It was found that the shape of the cathode significantly affects the duration of SAEB current pulse, its amplitude and shape. The largest amplitudes (≈ 90 mA) were observed with the tubular cathode at a pressure of air of 12.5 kPa. Saeb current pulse duration was $\tau_{0.5} \approx 130$ ps. Two pulses with different duration, amplitude and energy of electrons were observed with the needle cathode. When using the ball, the duration and amplitude of the beam current pulses were $\tau_{0.5} \approx 250$ ps and ≈ 4 mA, respectively.

Studies performed with a four-channel ICCD camera showed that the breakdown occurs via the development of streamers starting from the cathode. The diameter of the streamer depended on the radius of curvature of the cathode, and was the largest with the smallest radius of curvature (needle cathode). As the air pressure increased to 100 kPa, the amplitude of the beam current decreased.

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PARTICLE DYNAMICS IN QUADRUPOLE ALTERNATING CORONA DISCHARGE

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Particles dynamics inside alternating corona discharge electrodes of the trap was studied. Four electrodes were mounted parallel to each other at the corners of a square. At the electrodes prebreakdown alternating voltage was applied with phase π at neighboring electrodes. Uncharged Al2O3 microparticles were injected between the electrodes where they start gaining charges in alternating corona discharge. The frequency of the alternating voltage was 50 Hz and the strength of electric field was up to 30 kV/cm (peak-to-peak).

Under the assumption of wire-to-cylinder geometry of the electrodes and hydrodynamic model that takes into account the continuity equations govern the transport and the gain/loss balance of every species due to the chemical reactions with the Poisson equation a stationary corona discharge was simulated in oxygen [1,2] for different geometries, the distributions of positive and negative ions and electron were gained.

Using the distribution of electric field and concentration of ions and electrons in positive and negative corona discharges the particle's charges were calculated at every moment of simulation. Analyzing particle motion the areas of particle capturing (the geometric area, parameters of voltage and the geometry of electrodes, particles sizes and densities) and the dynamics of particles changes were found, Fig 1.

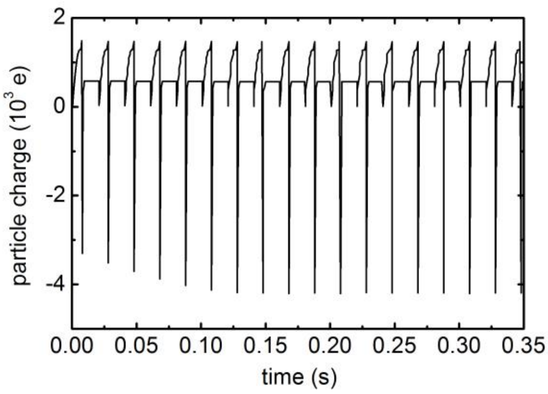

Fig. 1. The charge dynamics of 1μm Al2O3 captured inside quadrupole corona discharge.

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THE DYNAMICS OF IONIZATION WAVES FORMATION IN A TRANSVERSE NANOSECOND PLASMA-BEAM DISCHARGE WITH A SLOT CATHODE IN ARGON

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The paper presents the results of an experimental study and numerical simulation of the spatial-temporal dynamics of ionization processes in the gap between the electrodes and inside the cathode cavity during the formation of a nanosecond discharge in argon at pressures in the chamber from 1 to 10 Torr. The cathode had the shape of a cylinder with a diameter of 1.0 cm with longitudinal cuts 0.2 mm wide and 0.6 cm deep; the discharge area between the electrodes was limited by dielectric walls set at a distance of 0.2 cm from each other. Voltage pulses with an amplitude of 0.5 to 1.5 kV and a duration of about 100 ns were applied to the electrodes. The dynamics of the formation of the spatial structure of the discharge at various stages was experimentally investigated using high-speed photo-recording with a Princeton Instruments PI-MAX3 camera [1]. The correspondence between the density distribution of charged particles and the optical patterns of the discharge was established. A numerical model of the formation of a limited discharge in argon under various external conditions was constructed taking into account the influence of the charge deposited on the surface of the dielectric wall, the secondary electron emission coefficient from the cathode surface, and the influence of the space charge on the distribution of electric potential between the electrodes. The role of the surface charge deposited on the dielectric walls in the formation of the spatial structure of the discharge was established. The results of numerical simulation are compared with experimental data. It is demonstrated that the electron concentration in a discharge limited by dielectric walls is an order of magnitude higher than in an unlimited discharge under the same external conditions.

The general patterns of formation and development of a limited discharge in argon are discussed; the main physical processes affecting the dynamics and the spatial structure of the discharge are established.

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HOLOGRAPHIC INTERFEROMETRY FOR THE STUDY OF THE ELECTRIC EXPLOSION OF WIRES *

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Some experimental results of holographic interferometry [1] for the specification of an electric explosion of wires [2] are presented. "Slow" (during of 50…200 μs) electric explosions of thin (with an initial diameter of 20…50 μm) different metal titanium wires were characterized in air and argon atmosphere. An energy input from a capacitor into the wires was varied from 3 to 7 J. The process was studied with the double exposure laser (λ=532 nm) holographic interferometry.

The main features of the explosion were visualized at different times. A curvature of interference fringes indicated about a refractive index change (see Fig. 1.). So a generated shock wave (1), a shock compressed gas (2) and an extended high temperature explosion products (3) were found. At less times (<30 μs) an initial wire was still visualized (4). A complicated (with a heavy curvature of interference fringes) behavior of a refractive index in explosion products was explained by a presence of titanium small particles, neutral and ionized vapors, arc plasma, etc.

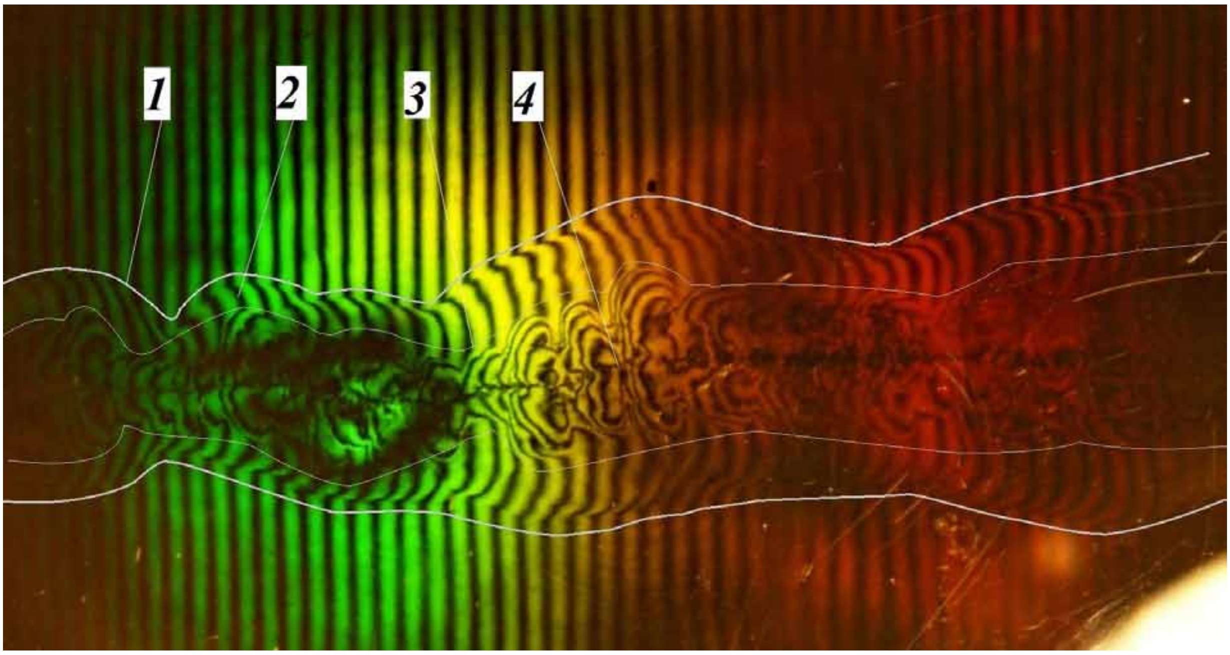

Fig. 1. Holographic interferometry pattern of titanium wire explosion at 20μs: 1 – shock wave front, 2 – shock compressed gas, 3 – explosion products and 4 – initial wire

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I-V CHARACTERISTICS AND EFFICIENCY OF ELECTRON BEAM GENERATION IN DISCHARGES, IN NITROGEN AND OXYGEN*

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Sources of electron beams (EB) with an EB of the keV-range energy based on a gas discharge typically use helium or argon, or their mixtures with oxygen. At the same time, there are practically no studies on the generation of EB in pure molecular gases, in particular, in nitrogen and oxygen. Such generators can be used in technological operations for nitriding and oxidation, for example, in semiconductor industries. Of particular interest is also the study of physical processes in high-voltage discharges in N_2 and O_2, the study of which may contribute to the expansion of possible applications.

The studies were carried out in carefully degassed cells with a titanium cathode with a diameter of 12 mm and an interelectrode distance of 21 mm. Calibrated thermal sensors were installed to measure the efficiency of the generation of EB on the side walls of the cell and on the anode-collector of electrons. The potential measurement of the electric field in the cathode region was carried out using probes. It turned out that in N_2 and O_2, the current – voltage characteristics have a smoothly increasing form in the investigated voltage range of 0.5–6 kV and pressures of 20–200 mTorr. Already at $U > 1.5$ kV, the efficiency η of the generation of EB exceeds 50% and increases to 86% at $U = 6$ kV for discharge in O_2 and 79% for discharge in N_2.

The achievement of such high efficiency is explained from the standpoint of the mechanism of kinetic emission of electrons under the influence of fast neutral and ionized molecular particles with a total emission coefficient of $<\gamma> = 6$ for discharge in O_2 and $<\gamma> = 3.8$ for discharge in N_2. In turn, the high $<\gamma>$ value is ensured by the effective interaction of fast molecular particles with the cathode surface. On the one hand, they saturate the surface layers to the level of packing density corresponding to the density of liquid oxygen and nitrogen. On the other hand, fast particles accelerated in the region of the cathode potential drop ionize nitrogen or oxygen in the surface layers, releasing electrons with subsequent emission. The greater magnitude of $<\gamma>$ and the efficiency of generation of EB in oxygen is explained by the large ionization cross section of the O_2 molecule with fast O_2 and O_2^{+} compared with the ionization cross sections of N_2, and fast N_2 and N_2^{+}.

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EMISSION CURRENTS FROM CATHODE WITH NANOSTRUCTURED TENDRIL BUNDLES

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Plasma-surface interaction is a key factor for realization of thermonuclear fusion with magnetic confinement. The experiments on plasma-wall interaction with tungsten have been carried out on linear simulators and tokamaks show that thin nanorods called “fuzz” can be formed on tungsten surfaces after helium plasma irradiation. The typical thickness of the fuzzed layer is ~1 μm, and the rod diameter is ~10 nm. It was demonstrated in [1] that in the case of fuzz formation frequency of unipolar arcing increases that leads to higher material erosion rate.

Recently it was shown [2] that nanostructured tendril bundles (NTB) demonstrated in fig. 1 can grow on the tungsten surface after neon or nitrogen addition to helium plasma. NTB can be several tens micrometers in height and about 10 μm in diameter near bottom. The NTB as a rule are separated by several hundred micrometers from each other and are formed from thin fuzz nanorods. The mechanism of NTB formation is not clearly understood [3,4] but in some way it is related to the sputtering and redeposition processes on surfaces covered by tungsten fuzz under plasma ions impact.

As for plasma-surface interaction with NTB covered cathode, it is of interest to investigate dynamics and parameters of emission currents in DC electric fields.

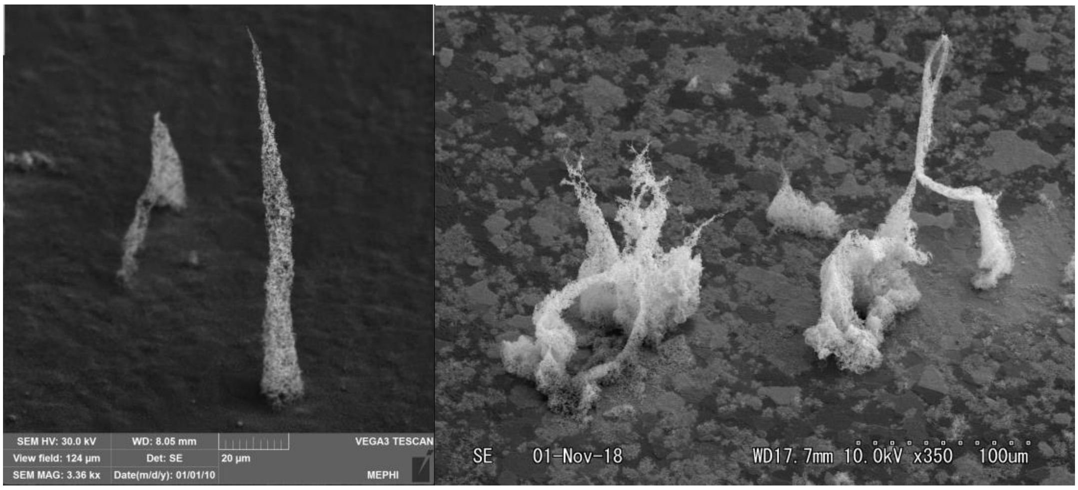

Fig. 1. Photos of different types of nanostructured tendril bundles on tungsten surface.

Field emission from samples with NTB was measured using vacuum diode device. Emission current of several nanoamperes was detected for electric fields lower than 1 kV/mm that is comparable with specially designed flat field emission cathode. Field enhancement factor and effective emission area were calculated using Fowler–Nordheim formula and compared for different types of the nanostructures. Transparent anode covered by luminophore was used for detecting of emission sites distribution on the surface and their dynamics during experiment. Emission sites positions were in strong correlation with position of the NTBs arrays on the cathode surface. In combination with analysis by scanning electron microscope and confocal laser microscope, this allows detection of nanostructures initiating of pre-breakdown currents. We have also seen a temporal evolution of emission currents and found that these currents do not directly relate to the evolution of NTB form. The possible reasons of such temporal currents behavior will be also discussed.

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STUDIES OF THE MECHANISMS FOR CONTROLLING THE SPATIAL PARAMETERS OF THIN PLASMA CHANNEL IN OPEN ATMOSPHERIC DISCHARGE*

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The project is devoted to a complex theoretical study of a new phenomenon in gas-discharge plasma physics - the so-called "apokamp discharge" (from the Greek "apo" + "kamp", that is, "from bending") [1]. Apokamp discharge is the phenomenon of formation in the open space of long and narrow plasma jet oriented perpendicularly to a short plasma column of a pulse-periodic contracted discharge.

The study included both experimental and theoretical parts. As a result of a series of experiments, the influence of an external electric field created by a grounded electrode on the formation and maintenance of the apokamp is shown. Note that the external field is the initiator of the jet, but does not affect its orientation in space. The average external electric field, at which a plasma jet grow up, is determined in experiment.

The model of the phenomenon is constructed in the framework of the hydrodynamic approach with drift-diffusion approximation. For the first time, the problem of a theoretical description of the appearance of a narrow plasma channel growing up perpendicular to the high-current channel of the main discharge has been solved. The effect of the weak external field on the formation and growth of the plasma channel is theoretically demonstrated.

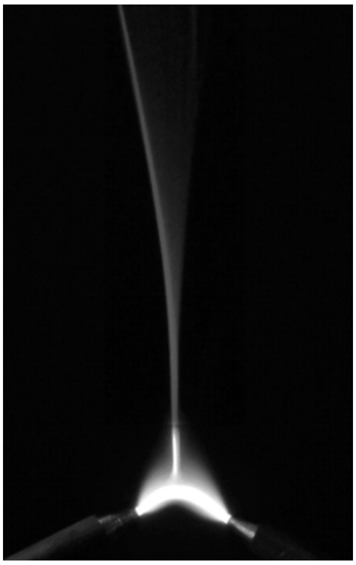

Fig. 1. Apokamp between a sharp-ended electrodes.

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SIMULATION OF THE EXPLOSION OF A SURFACE MICROPROTRUSION DURING A RADIO FREQUENCY BREAKDOWN

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The explosion of a surface microprotrusion under the action of a radio frequency electromagnetic field has been numerically simulated. It has been demonstrated that the microexplosion and the subsequent crater formation occur in much the same way as they do in the case of a dc field. The results obtained support the hypothesis that a dc vacuum breakdown and a breakdown initiated by an rf wave incident on a metal surface proceed by the same mechanism [1, 2].

This work was supported in part by the Russian Foundation for Basic Research (grants Nos. 17-08-01282, 19-08-01004, 17-08-00459); by the RAS Presidium (basic research program I.11P); Scholarship of the President of the Russian Federation Grant No. SP- 300.2019.1.

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REGULATION OF THE AIR HIGH VOLTAGE AC PLASMA TORCH POWER BY SMALL AMOUNT OF METHANE*

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Already for a long time plasma torches are used for a wide range of areas: welding and cutting of metals and refractory materials; the application of protective coatings on various materials; obtaining nanodispersed powders of metals and their compounds; thermal neutralization of highly toxic organic waste; oil-free kindling of pulverized coal boilers of power stations.

In each case, the most important parameter of the plasma torch is its power. In most cases, the power of an electric arc plasma torch can be changed by several methods: electric current, voltage, mass flow rate of the plasma-forming mixture, composition of the plasma-forming mixture. Previously it was found that in plasma torches with a vortex stabilization of an electric arc for plasma-forming mixtures consisting of steam, carbon dioxide and methane, the power increased significantly with the additional methane [1]. This was due to the formation of hydrogen:

$$CO_2 + CH_4 = 2CO + 2H_2 \quad (1)$$

$$H_2O + CH_4 = CO + 3H_2 \quad (2)$$

The power of the plasma torch varied from 60 to 170 kW. In this case, the voltage drop across the electric arc was changed. This is due to a change in the electrical conductivity of the arc containing hydrogen and an increase in the intensity of heat exchange between the arc and the colder gas vortex stabilizing it.

The report deals with the AC three-phase high-voltage plasma torch [2]. A small amount of methane (up to 1%) was added to the main plasma gas. In this case, the following reaction took place in the electric arc burning zone:

$$CH_4 + 0.5O_2 = CO + 2H_2 \quad (3)$$

The plasma torch is powered by an alternating current power source with a 10 kV open circuit voltage [7]. The power supply consists of a high-voltage transformer (380/10000V), current-limiting inductances, a reactive power compensator and a system for continuous measurement of electric parameters.

However, unlike the mixture of methane with steam, the power of the plasma torch increased exponentially. Probably the main cause of this phenomenon is the decomposition of nitrogen oxides, the ions of which provide a significant portion of the electrical conductivity of the electric arc:

$$2NO + 2H_2 = N_2 + 2H_2O \quad (4)$$

The same experiments were carried out using a plasma torch with two inputs of plasma-forming gases [3]. Air was supplied to the near-electrode zone, and a mixture of air and methane was fed to the electric arc zone. In this case, the power change was significantly lower. This is since there is no hydrogen in the electrode area and the main sources of electrical conductivity are preserved. The results indicate that it is possible to control the power of the plasma torch without a significant change in the total flow rate of the plasma-forming mixture and its composition.

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TARGET TEMPERATURE MEASUREMENTS IN A PULSED MAGNETRON DISCHARGE IN TARGET MATERIAL VAPOR*

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Nowadays, magnetron sputtering plays one of the leading roles in deposition of thin films with outstanding physical properties and high quality. Comparing magnetron sputtering with other methods of physical vapor deposition, we can distinguish a number of significant drawbacks, one of which is the low efficiency of the film deposition process and low film growth rates. To eliminate the drawbacks of magnetron systems, various modifications of existing systems are being developed. One of such promising concepts is pulsed magnetron discharge in target material vapor [1, 2].

The main parameter to assess the effectiveness of the modified magnetron sputtering system is the deposition rate The deposition rate, in turn, is influenced by the shape of the current pulse profile, voltage, discharge temporal characteristics and temperature of the target [3]. The measurement of the target temperature is the most problematic part of the evaluation of parameters affecting the deposition rate.

There are two different ways to measure temperature: contact and non-contact [4–5]. At significantly high temperatures of heated objects, the use of the contact method for temperature measurement is complicated. Contactless temperature analysis in our case is also difficult, because of the rapid deterioration of optical transmission due to high speed of coating deposition.

As part of this work, a special shielding that allows optical emission measurements from hot Cu, Si, and Cr targets has been designed. Comparison of optical and contact temperature measurement methods has been performed. The methods and devices described in this contribution aim at investigating the dependence of the deposition rates of Cu, Si, and Cr films on the impulse shape of the discharge current and voltage, and the discharge plasma temporal characteristics.

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DBD PLASMA JETS IN ARGON AND HELIUM: STREAMERS PROPAGATION ALONG GAS FLOWS*

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Atmospheric pressure plasma jets (APPJ) are one of the most prospective sources of "cold" atmospheric plasmas that have been intensively developed for a wide range of biomedicine applications. To generate APPJ, we used a dielectric-barrier discharge, which was fed by an original high-voltage signal consisting of a superposition of 40 kHz bipolar square pulses and 300 kHz oscillating signals (Fig. 1(a)).

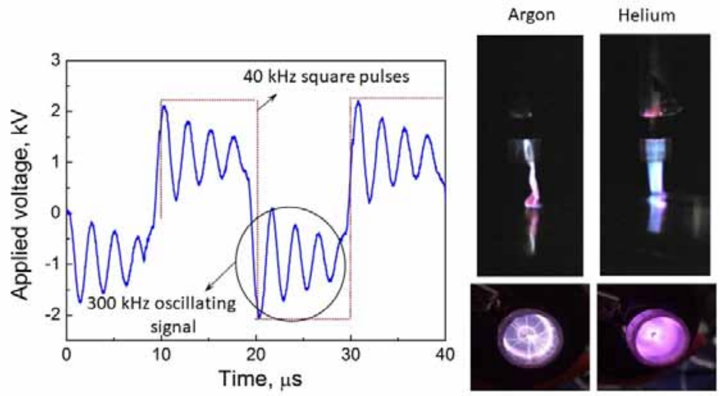

Fig. 1. High-voltage signal to feed a dielectric-barrier discharge in a helium flow (a); images of a dielectric barrier discharge in argon (left) and helium (right) flows (b).

DBD was ignited inside a quartz tube with a co-axial electrode system "inner rode – outer ring". The high voltage applied to the inner electrode, which was made of a copper wire 1.5 mm in diameter. The outer electrode made from a copper foil stripe was grounded. Gas flow was passing through the tube with the discharge with the gas flow rates of 1, 3, and 4.5 l/min, a plasma jet appeared in ambient air. Plasma jet is formed due to the ionization waves (streamers) propagation along the gas flow outside the discharge tube. The shape and geometrical sizes of the plasma jet depend on the combination of the applied voltage parameters and gas-dynamics conditions.

Argon and helium are two inert gases wide-spread in plasma technologies, which are used in APPJ-type generators to produce "cold" plasma flows. Owing to the different nature, the two gases provide DBD burning on the different regimes: diffusive and filamentary (Fig. 1(b)) [1]. Electrical diagnostics of the discharge was done along with the high-speed imaging of the plasma jets.

Electrical measurements suggest that diffusive nature of helium discharge gets along with the narrow single discharge current peaks of 10 mA at the positive and negative half-periods of the applied voltage, whereas the filamentary structure of argon discharge is recorded along with the numerous small peaks of the discharge current that almost indistinguishable against the displacement current.

The time-spatial behavior of the streamers along the helium and argon plasma jets has been described. For the helium plasma jet, a special step-by-step streamer propagation mechanism was recorded. It is valid when the applied voltage has a special shape with a voltage bias of oscillations. For the argon plasma jet, a branched structure of the streamers was observed. It is due to the filamentary regime of DBD burning in argon.

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THE METHOD OF SYNTHESIS GAS AND STEAM PYROLYSIS AT HIGH TEMPERATURES

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Recently, quite a lot of publications have been devoted to the improvement of methods and approaches to the use of hydrocarbons in the energy sector and other non-volatile industries. Consider a historical method of producing fuel based on steam pyrolysis. This method according to the official version belongs to Traverse Morris Williams (England, 1927). This water gas is obtained by blowing water vapor through a layer of hot coal or firewood. The reaction follows the $H2O + C \rightarrow H2 + CO$ equation with heat absorption - 132 kJ / mol.

As a known at temperatures approaching 1000 ° C, water is decomposed into hydrogen and oxygen. While the water in a fire heats up and evaporates, it takes a large amount of heat and acts as a "quencher", but as soon as the steam heats up above 400 ° C, the water turns into additional fuel. This method of obtaining energy is undeservedly forgotten and received its applied distribution only in the narrow field of metallurgy and in chemical synthesis - for the production of synthetic fuels, lubricating oils, ammonia, methanol, etc.

The main value of this method of producing fuel lies in its availability of investments and the simplicity of manufacturing working devices for the general population and production. Given the conditionally zero cost of water, as well as the way it is processed (decomposed), you can move from the concept of alternative fuel to the concept of increasing the efficiency of burning traditional fuel.

This article describes how to increase the efficiency of a coal (wood burning) stove or solid fuel boiler without using additional hydrocarbon energy resources. The principle of operation of the technology is quite simple: water from the tank (steam generator) is converted into steam with a high temperature (300–350 ° C) and is fed directly into the flame through a nozzle, acting as a kind of combustion catalyst, increasing the productivity of the heating installation.

REGIMES OF SUSTAINING THE HOLLOW-CATHODE GLOW DISCHARGE WITH THE HOT FILAMENT INSIDE THE CAVITY*

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Nowadays hollow-cathode low-pressure glow-type discharges are widely used for different applications [1-5]. In particular, such discharges are used for generation of charged particle beams, for surface modification, for generation of extreme ultraviolet radiation, in high-current switching devices (cold-cathode thyratrons), for generation of large volume plasmas and so on. The term "low-pressure" implies that the discharge conditions correspond to the left branch of the Pashens curve, i.e., the electron mean free path in terms of ionization exceeds the length of the discharge gap. Under these conditions, single electrons cannot initiate the gap breakdown.

The conventional approach to explain the mechanisms of sustaining of the low-pressure glow discharge implies that the main part of the discharge current at the cathode surface is carried out by ions and electrons are emitted from the cathode due to the ion bombardment [6]. To constructing the model of a hollow-cathode discharge the conventional secondary emission yield γ from the cathode material – the number of secondary electrons per one ion incident on the cathode surface is often used.

The coefficient γ formally takes into account only electron emission caused by the ion bombardment of the cathode surface as the secondary process. This coefficient is sometimes called the generalized emission yield, implying that it also takes into account the photoeffect. However, the coefficient γ can be used to describe the emission current caused by the photoeffect and ion bombardment only if both components of the emission current depend equally on the ion current. In most cases, such a situation is an exclusion rather than a rule and it is physically more justified to consider the electron photocurrent as a certain external current. Then, an external emission source should be introduced separately.

Such approach was proposed in [7-11]. In these papers the generalized coefficient of secondary emission Γ, that depends on external emission current and includes classical coefficient γ, was introduced. Based on this approach the explanations of discharge sustaining features in the main gap and in the trigger unit of the cold-cathode thyratron were done.

At the same time, there are other types of discharges for that the proposed approach for explanation of the mechanisms of current passage and discharge sustainment seems to be perspective. It can be spread to the discharges in devices for the modification of properties of material surfaces. In such devices, the low-pressure discharge is sustained and external emission current is set and changed artificially. In particular, to this type of discharge can be attributed the glow discharge with a hollow cathode and hot filament (thermionic cathode) inside the cavity [5, 12].

In this report the results of investigations of hollow-cathode glow discharge with the hot filament inside the cavity are presented. Current-voltage characteristics for the different filament currents were recorded. The regimes of discharge sustaining based on the model are interpreted. It is shown that the model agrees with experiments.

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INFLUENCE OF THE RESISTANCE OF SEMICONDUCTOR ON DELAY TIMES TO BREKDOWN IN A FLASHOVER BASED TRIGGER UNIT OF THE COLD-CATHODE THYRATRON*

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Currently, high-current switching devices based on low-pressure hollow-cathode pulsed discharge (so-called pseudospark switches) are widely used [1-5]. The design and principle of operation of these switches are close to those of a classical hot-cathode hydrogen thyratrons. However, these devices do not have a hot cathode. Therefore, pseudospark switches are often called cold-cathode thyratrons or thyratrons with a grounded grid [3, 6].

As in the case of classical thyratrons, a range of operating pressures of the switch corresponds to the left branch of Paschen's curve. Under these conditions the electron free path for ionization is much in excess of the electrode separation. For both self-breakdown of the main gap of the thyratron and for external discharge triggering a considerable pre-breakdown electron current is required [7, 8]. For the case of external triggering, this current is provided due to a special trigger unit that is placed in the main cathode cavity. In the sealed-off thyratrons, that are produced commercially, trigger units are based on auxiliary glow discharge (TPI series) and on a discharge over a semiconductor surface (TDI series) [6].

Trigger unit is intended for plasma generation inside the thyratron cathode cavity at a curtain instant of time. To do this, a voltage pulse with an amplitude of several kilovolts (trigger pulse) is applied to one of the electrodes of the trigger unit. For the case of trigger unit based on discharge over the semiconductor surface, after application of a trigger pulse the current in a trigger circuit at the initial stage is flowing through the semiconductor body. Due to the current cathode spots arise in the place of contact of trigger electrode and semiconductor and surface discharge is initiated. At the further stage, surface discharge current is intercepted from the trigger unit to the main cathode cavity and due to the hollow cathode effect plasma is generated inside the cavity [9, 10]. Electrons are extracted from the plasma into the main gap that leads to initiation of the discharge in the main gap and thyratron triggering occurs.

Time interval from the application of trigger pulse to initiation of breakdown in the thyratron main gap is the delay time of thyratron triggering. This delay time consist of the delay time to initiation of surface discharge, delay time to interception of the surface discharge current to the main cathode cavity and delay time to discharge development in the main gap. In turn, the delay time to initiation of surface discharge have to depend on the value of semiconductor body resistance and on the trigger pulse amplitude and rise time.

In this report the results of investigation of the trigger unit based on a discharge over the semiconductor surface with different resistance of semiconductor body and different amplitudes of a trigger pulse are presented. Experiments were carried out with the sealed-off thyratrons of TDI series. Data on delay times to discharge initiation were obtained. Methods for reduction of the delay time to current interception to the main cathode cavity are proposed. Conditions of thyratron operation for that the delay times of thyratron triggering are minimal revealed.

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OPERATION FEATURES OF THE PULSE PENNING ION SOURCE IN THE TRANSITION PRESSURE RANGE

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The ExB gas discharge (penning discharge) is widely used in various fields of science and technology [1]. In particular the penning discharge is effectively used in ion sources (IS) for the miniature linear accelerators [2].

There are several modes of the penning discharge combustion depending on the physical parameters (anode voltage, magnetic field magnitude, working gas pressure) [3]. The discharge mode significantly affects the potential and the electron density distributions inside the discharge cell as well as the speed of discharge development and, as the consequence, the ion beam density and the efficiency of the ion extraction. For the stable operation of the IS the linear dependence of the discharge current (and the extracted ion current) on the working gas pressure is required. For the pulsed IS it is also important to insure the rectangular shape of the extracted current pulse with short leading and trailing edges, which do not change its shape in a given pressure range [4]. Therefore, the “transition” mode of combustion characterized by the decrease in the discharge current (and the extracted ion current), followed by a sharp exponential increase in current with a gradual increase in pressure is especially undesirable. The pressure range in which the conditions for the "transition" mode are realized depends on the magnitude of the magnetic field, the anode voltage and the geometric parameters of the discharge cell and is usually in the range of ~ 0.5 – 10 mtorr.

The paper presents the results of experiments studying the dependence of discharge and extracted currents on the pressure of pulsed penning IS, which was described in [5]. A comparative analysis of the amplitude-time and current-voltage characteristics of IS for the various anode voltage amplitudes, pulse repetition rates, pulse durations, magnitudes (and configurations) of the magnetic field is presented. The obtained results reveal the existence of different (stable and unstable) discharge modes depending on the operating conditions of the power supply system and the pressure range of the working gas (deuterium). The features of current waveforms in the transitional pressure range 0.5-2 mTorr (see figure 1) are defined.

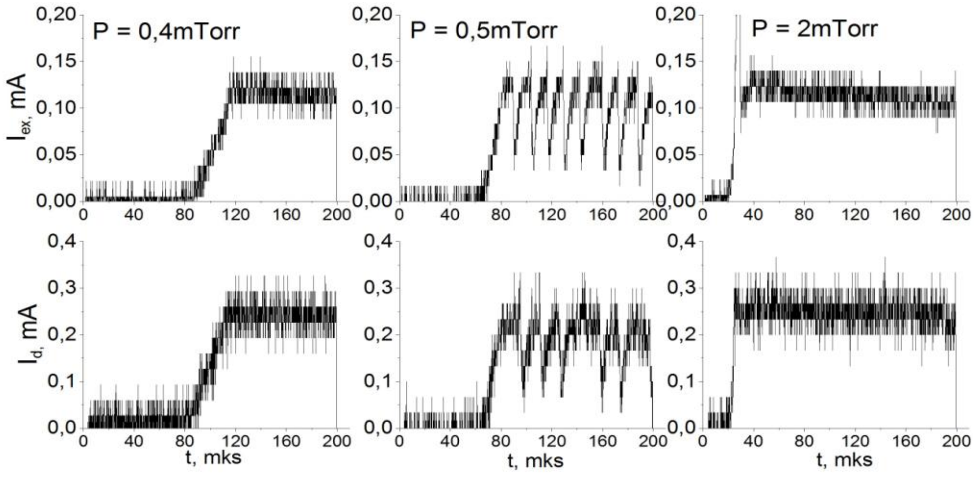

Fig. 1. Current pulse waveforms examples in the transient pressure range (I_d - discharge current, I_{ex} - extracted ion current). The anode voltage is 2 kV, the frequency is 600 Hz and the duration is 200 μs.

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ATMOSPHERIC PRESSURE PLASMA GENERATOR FOR MODIFICATION OF NITRILE BUTADIENE RUBBER SURFACE*

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The atmospheric pressure discharge like a "plasma jet" which operates in the flows of nitrogen N_2 as well as carbon dioxide CO_2 were investigated. The peculiarities of plasma generator operation with different materials of discharge system electrodes were investigated also. It was experimentally determined that the use of a tantalum cathode and a copper anode delivered stabile operating of the discharge. Exactly at these electrode materials the dependences of the discharge voltage vs the discharge current were obtained.

The optimal operating conditions were as follows: both N_2 and flow CO_2 rate of – up to 5 l/min; operating mode - DC or pulse; discharge voltage magnitude – about 600 V; discharge current magnitude – about 80 mA; pulse duration – up to 10 µs; pulse repetition rate – up to 200 kHz. The single Langmuir probe was used for diagnostics at these discharge parameters. As the result of probe diagnostics, the values of the electron temperature T_e and plasma density n were obtained. T_e was about 1.75 and 5 eV and n was about $9\cdot10^{10}$ and $1\cdot10^{10}$ cm^{-3} for N_2 and CO_2 plasmas respectively.

This plasma generator was used for modification of the nitrile butadiene rubber (NBR) surface modification. After plasma treatment, the structure and tribological properties the surfaces of NBR samples were studied. The criteria for influencing the friction resistance reduction and mechanical wear of the NBR surface were determined.

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PLASMA SOURCES AND EQUIPMENT

ABOUT THE PULSE MODES OF CORONA GLOW AREA*

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Corona discharge is one of the varieties of gas equipment, and its use can often be found in electrostatic filters, as well as in electro-gas-dynamic automation devices. Usually, a corona discharge is observed under conditions of sharply inhomogeneous electric fields [1, 2], in which a high field strength is achieved and its rapid decline with increasing distance from the ionization site, which prevents electrical breakdown of the gas-discharge gap.

The purpose of this work is to determine the current modes and the corona discharge form in air using an electrode with a small curvature radius.

The studies were carried out in atmospheric air ($p \approx 760$ Torr), with a constant voltage of both various sizes polarities. For the local electric field amplification, a thin needle 5 cm long, 0.32 mm in diameter, a tip radius of 40 μm and a tip angle of 9.5° was used as a high-voltage electrode. The corona discharge was ignited both at a separate electrode and between the tip and flat electrodes with a discharge gap of 1 to 4 cm. A flat electrode measuring 16x16 cm was used to facilitate the registration of the corona discharge current. The voltage at the electrode was supplied from high-voltage DC sources of positive or negative polarities with voltage $U_p \leq 25$ kV. Using a TDS 3034 oscilloscope (Tektronics, Inc.), the time characteristics of the voltage and discharge current were recorded.

At a positive voltage and an interelectrode gap of 2 cm, the ignition of a corona discharge was observed with $U_p \approx 5$ kV. At the electrode a «low-luminous cloud» appeared, the size and intensity of which grow with increasing voltage. $U_p < 9.8$ kV provoked the formation of streamer coronas, the length of which increased, in consequence of which they reached a flat electrode at voltages of about 13 kV. An increase in voltage above 15 kV led to the formation of a diffuse (glow) discharge, and then a spark discharge.

The amplitude of the discharge current pulses for positive polarity reached ~ 700 μA, which is two orders of magnitude greater than the negative one. This difference is explained by the absence of a streamer corona at a negative voltage polarity. The results of size measurements of the spherical-like corona glow area with a negative polarity showed that its dimensions also increase with grow voltage, but have a larger diameter than the positive-polarity corona with an equivalent voltage. The minimum ignition voltage of the negative corona was ~ 3.1 kV with an interelectrode gap of 2 cm.

The peculiarity of the negative-polarity spherical corona is the registration of repetitively pulsed current pulses (Trichel's pulses), following with a high frequency in a wide voltage range. The amplitudes of the discharge current pulses with negative polarity didn't change significantly with increasing voltage, but the pause between the pulses decreased. It can be noted that the current pulse duration at half-height with a negative voltage on average was about 180 ns in the voltage range of -3.1 ... -12 kV, and at positive-polarity voltages, in the range of 11.2-13.6 kV, this value was ~ 250 ns.

Studies of the corona discharge emission spectra confirmed that the bands of the second positive nitrogen system in the UV area of the spectrum have the greatest intensity.

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PLASMA PARAMETERS OF DUAL DEEP OSCILLATION MAGNETRON SPUTTERING SYSTEM[1]

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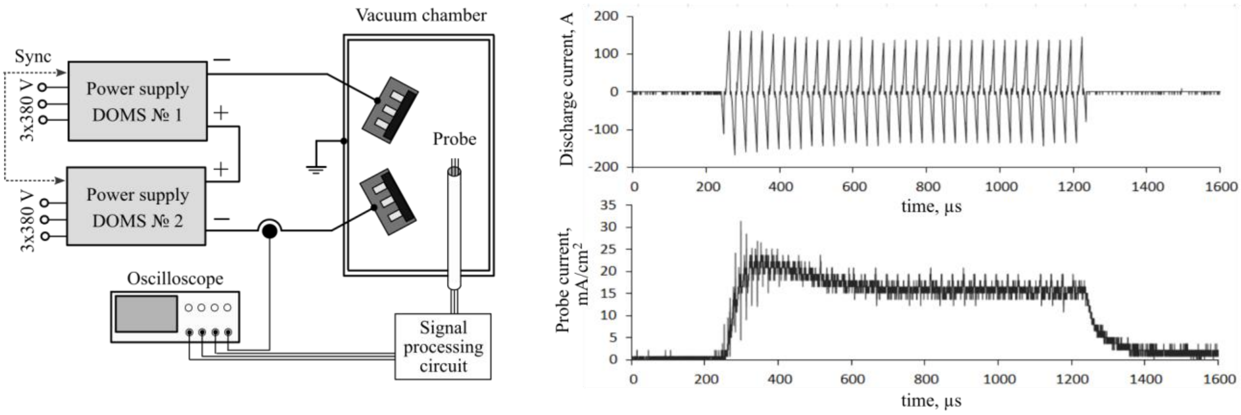
Deep oscillation magnetron sputtering (DOMS) is a new type of high power pulsed magnetron sputtering technology (HPPMS or HIPIMS) that allows to prevent the formation of arcs in the processes of reactive magnetron sputtering [1,2]. The report presents the results of an experimental study of the discharge formed by dual magnetron sputtering system (DMSS) with aluminum targets in the DOMS regime. To power the dual DOMS discharge, high-power bipolar microimpulse packages are used, which form a macroimpulse with a duration of 1000 ÷ 3000 μs, as shown in Fig. 1,b. Figure 1,a shows the connection diagram for DMSS, pulse power supply and measuring devices. Plasma parameters, such as electron temperature, electron concentration, the floating potential, plasma potential and ion current density on the probe were measured using triple and single Langmuir probes. Their dependences on the parameters of the discharge pulse power supply (voltage and current amplitudes, current density and power density on the target) were established. The use of dual DOMS regime allowed 5-fold increase of the discharge current density and 20-fold increase of the discharge power density, relative to DC and middle-frequency magnetron sputtering. The plasma concentration at a distance of 12 cm from the target surface reached a value of $7\cdot10^{11}$ cm^{-3}, and ion current density – 18 mA/cm^2. The decrease in the sputtering rate of aluminum by 70% together with an increase in the ion current density caused an increase in the degree of ion impact on the substrate, which is determined by the ratio of the ion flux density to the neutral atom flux density. In dual DOMS regime, this parameter is equal to 0.28, whereas, in traditional sputtering modes with the same average discharge power, it was approximately 0.01.



(a) (b)

Fig. 1. a) Experimental setup; b) Waveforms of target current and ion current density on the probe.

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PLASMA SOURCE FOR GENERATION OF AUXILIARY ANODE PLASMA IN ELECTRON SOURCE WITH GRID PLASMA CATHODE*

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Intense electron beams sources are used in technologies for material surface treating. Insufficient electrical strength of the accelerating gap is the limiting factor of the introduction of plasma electron sources into the industry. In the paper [1], the authors used a discharge in the field of electron beam transportation to solve this problem, which allowed pre-ionization of the working gas before the start of beam generation.

In this work, we used an electron source with grid stabilization of the emission plasma boundary with a grid diameter of 40 mm and an operating beam current of up to 300 A [2]. The electron source is placed in an external magnetic field of 50 mT, in which studies of the operation of the discharge cell were carried out to create an auxiliary anode plasma based on an electrode system with a closed electron drift. The discharge cell had an annular anode with an inner diameter of 95 mm, located between two cathodes-magnetic conductors and a hollow cathode, the role of which was performed by the drift tube of the source. This discharge cell was introduced into the drift space of the electron beam at a distance of 10 mm or 70 mm from the emission grid of the plasma cathode, providing a discharge current of up to 3 A. It is shown that the most successful arrangement is the configuration of the electrodes of the auxiliary discharge cell, which is 70 mm from the emission grid. In this case, there is a constructive additional cathode, which can flaw the discharge current. Due to this, a plasma is created in the drift space, which makes it possible to close the current not only to the anode of the discharge cell, but also to the collector. As a result, the discharge current increases many times.

It has been established that even a weak discharge current (up to tens of milliamperes) makes it possible to reliably initiate the main arc discharge of the plasma cathode with a lower working pressure, reaching 7.2×10^{-3} Pa.

It was also established that the presence of the auxiliary discharge of several amperes makes it possible to improve the conditions for the generation of an electron beam at a low (less than 1.6×10^{-2} Pa) pressure in the first 15 μs of the source work. First of all, the improvement is due to the disappearance of high-frequency oscillations of the beam current.

In addition, the use of the auxiliary plasma anode reduces the training time of the accelerating gap due to ionic cleaning of the emission grid, which opens up new technological possibilities for electron sources of this type.

PLASMA SOURCES AND EQUIPMENT

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PLASMA GENERATION IN THE ARC DISCHARGE WITH A THERMIONIC CATHODE IN CURRENT STABILIZATION CONDITIONS*

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The features of the operation of the plasma generator with a thermionic and hollow cathodes "PINK" in the discharge current stabilization conditions are investigated. The possibility of not completely closing of the thermionic electrons current into the external circuit under these conditions is shown. In this case, the electron current closes inside the device, inverting the hollow cathode current increasing the thermal load on the electrodes (fig. 1). The effect of the filament current intrinsic magnetic field on the discharge voltage waveform is also shown [1]. The main characteristics of the plasma in different phases of the filament current were also investigated.

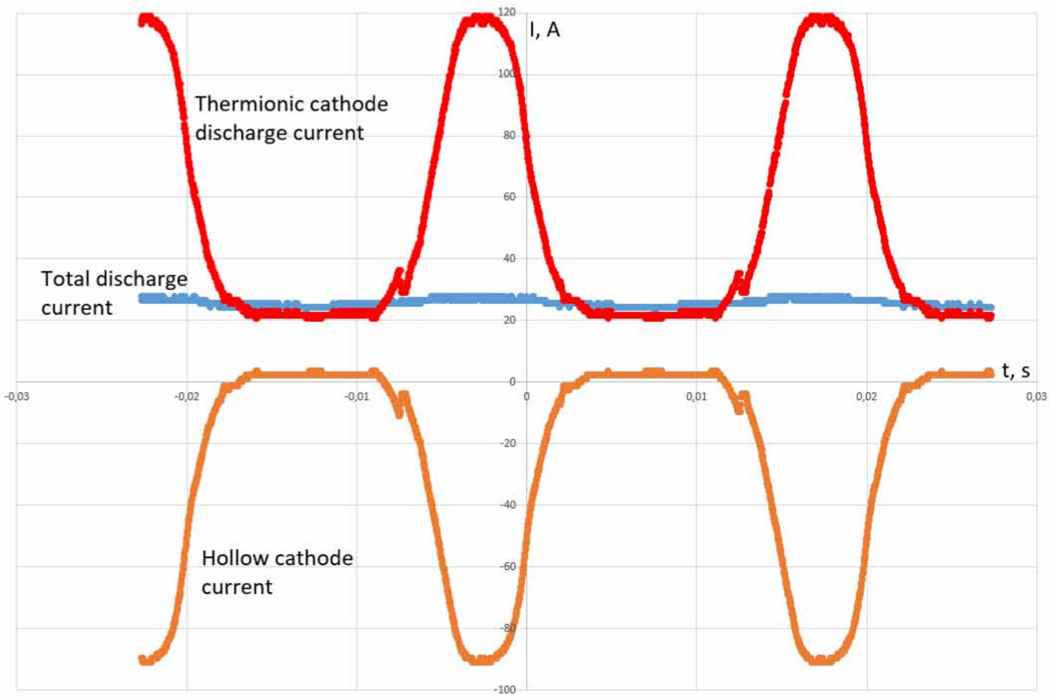

Fig. 1.Typical PINK current diagram.

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PLASMA SOURCES AND EQUIPMENT

LOW-TEMPERATURE PLASMA GENERATION IN A NON-SELF-SUSTAINED GLOW DISCHARGE WITH A HOLLOW CATHODE OF EXTENDED AND COMPLEX SHAPE*

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A new method for processing the inner walls of curvilinear extended cavities, including pipes has been developed. A two-stage system for plasma generation at low pressure (0.2 – 1 Pa), was used. The main non-self-sustained glow discharge with a hollow cathode generates a working plasma in the cavity being treated. An auxiliary discharge plasma produced by the "PINK" plasma generator [1-3], was the source of electrons for stable ignition and burning of the main discharge. The curvilinear extended cavity for plasma generation was a tube made of stainless steel 12X18H10T (AISI 321) with a total length of 300 mm and an internal diameter of 25 mm, bended over at an angle of 90° in the middle. The inner surface of the tube was a hollow cathode of a non-self-sustained glow discharge, and the anode was a tungsten rod 4 mm in diameter, inserted through the end of the pipeline for a length of 40 mm. To determine the uniformity of inner surface nitriding, 5 samples of the same steel with a diameter of 6 mm were placed at an equal distance from each other. In the experiment on nitriding, the main non-self-sustained glow discharge burned at a voltage of 200 V and a current of 4 A, and the auxiliary discharge current of the plasma generator "PINK" was 2 A. The pressure of the gas mixture (Ar:N2 = 10:1) was 1 Pa. In this discharge burning mode, the temperature throughout the curved pipeline was in the range of (600 – 650) °C. After nitriding for an hour, the thickness of the modified layer was (50 – 60) μm, and the surface hardness increased from 2.6 GPa to 7 GPa. The proposed discharge system allows to achieve good homogeneity (Fig. 1) of the temperature distribution (± 3% of the average value) and the thickness of the modified layer (± 8.5 % of the average value).

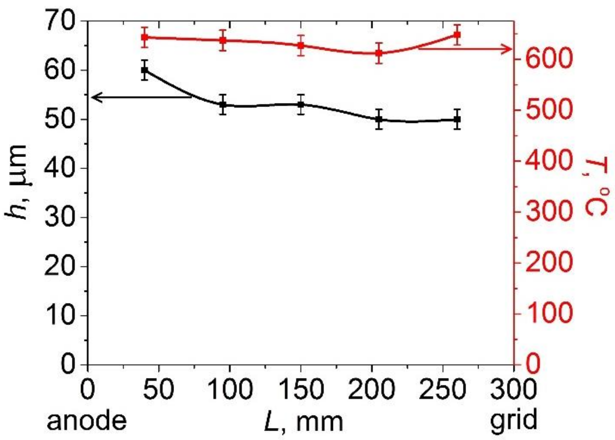

Fig. 1. The dependence of the distribution along the length of the cavity *L* of the thickness of the nitrated layer *h* and the temperature *T* in the curved cavity.

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ELECTRON BEAM GENERATION WITH VARIABLE CURRENT AMPLITUDE DURING ITS PULSE IN A SOURCE WITH A GRID PLASMA CATHODE*

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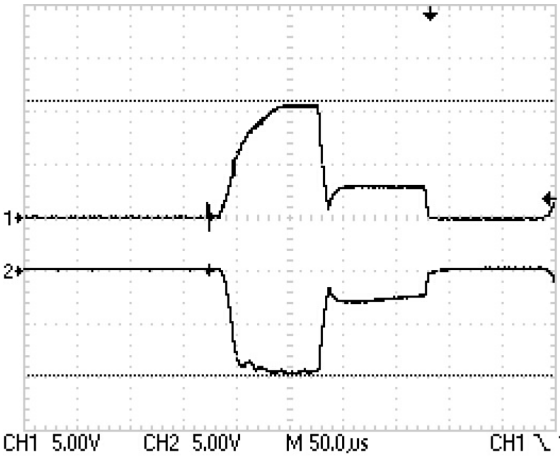
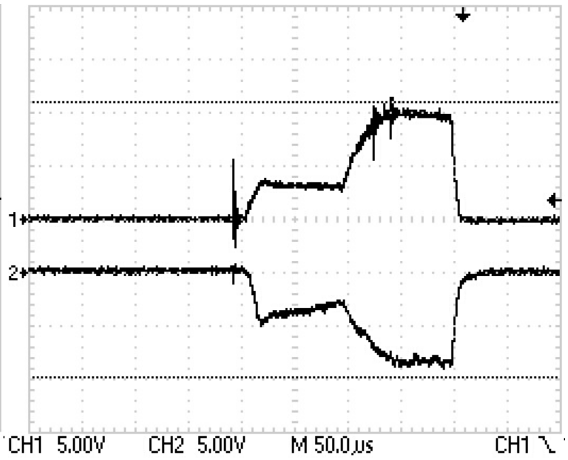
In electron sources with grid plasma cathodes, the boundary of the emission plasma is stabilized by a fine-structured grid, the cell size of which is comparable to the size of the Langmuir layer [1]. The correct choice of the cell size of the emission grid allows to stabilize of the emission plasma boundary, reaching a wide range of adjustment of the parameters of the generated electron beam with a weak dependence of these parameters on each other [1, 2]. Since the beam current amplitude is most often controlled by a proportional change of the discharge current in the plasma cathode, which allows to change the emission plasma concentration, this paper is investigated the possibility of generating the electron beam having variable amplitude by predicting the change in the discharge current amplitude during its pulse.

Figure 1 shows the characteristic oscillograms of the discharge current and the beam current obtained at the electron source «SOLO» included in the list of unique installations of Russia «UNICUUM». It can be seen from the oscillograms that the above-described advantage of plasma cathodes makes it possible to obtain electron beams with both a falling and a rising current amplitude of the beam during its pulse.

The obtained electron beam generation regimes open up new possibilities for using this source for both scientific and technological purposes.



a)



b)

Fig. 1. Осциллограммы тока разряда (*1*) и тока пучка (*2*), полученные в источнике электронов с сетчатым плазменным катодом «СОЛО». Масштаб: по вертикали – 100 А/дел., по горизонтали – 50 мкс/дел..

Fig. 1. Oscillograms of the discharge current (*1*) and the beam current (*2*), obtained in the electron source «SOLO» with a grid plasma cathode. Scale: vertical - 100 A/div., horizontal - 50 µs/div.

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IMPROVING THE UNIFORMITY OF THE DISTRIBUTION OF PLASMA CONCENTRATION IN THE NON-SELF-SUSTAINING LOW-PRESSURE GLOW DISCHARGE WITH A HOLLOW CATHODE[1]

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Electron-ion-plasma technologies for modifying the surface of materials due to their environmental friendliness and the feasibility of processing effects unattainable for other methods are widely used in industry [1]. In a number of works it was shown that the rate of nitriding in the plasma of low pressure discharges (≈ 1 Pa) can increase up to several times as compared with nitriding in an anomalous glow discharge [2-3]. This is due to the better cleaning of the surface of products from oxide layers in the plasma of low pressure discharges due to higher ion energy. However, to date, low pressure discharges have not found wide application for the chemical-thermal treatment of large-sized products due to problems in scaling, i.e. difficulties of homogeneous plasma generation in large vacuum volumes. A non-self-sustaining low-pressure glow discharge with a hollow cathode with the injection of an electron current of up to several tens of amperes makes it possible to achieve a plasma concentration of about 10^{18} cm^{-3} at a pressure of about 1 Pa with a degree of radial non-uniformity of about 13% in the volume of the vacuum chamber ~ 0.2 m^3, measuring about 600 × 600 × 600 mm [4]. In this work, studies were conducted to determine the effect of the hollow cathode material, the shape and location of the glow discharge anode on the azimuthal distribution of plasma concentration in the hollow cathode volume. During the experiments, hollow cathodes of steel grade 12X18H10T, titanium grade VT1-0 and with a surface coated with titanium nitride were used. The experimental results showed a significant influence of the shape and location of the anode on the degree of non-uniformity of plasma concentration.

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THE FORMATION OF POWERFUL PLASMA BUNCHES IN HIGH-CURRENT PLASMA GUNS WITH A DISCHARGE ON THE SURFACE OF THE DIELECTRIC*

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The paper presents the results of a study of the characteristics of plasma flows formed by high-current discharges over the surface of a dielectric capillary made of polyethylene, teflon and ceramics. In the experiment, the diameter and length of the capillary, the amplitude of the current (from several kA to tens of kA), the rate of current rise (τ_f – 250 ns, 420 ns, 1200 ns), the form of the current (oscillatory or aperiodic discharge mode) were varied. The optical and probe diagnostics were used to measure the plasma flow velocity. The probes were placed at a distance of 80, 130, 180 mm from the plasma guns (PG) (Fig. 1). The plasma flow velocity was measured by the time shift of the characteristic parts of the signals from the two probes. For optical diagnostics, a two-frame electron-optical complex "Nanogate Frame-9" with an exposure time of 20 ns was used.

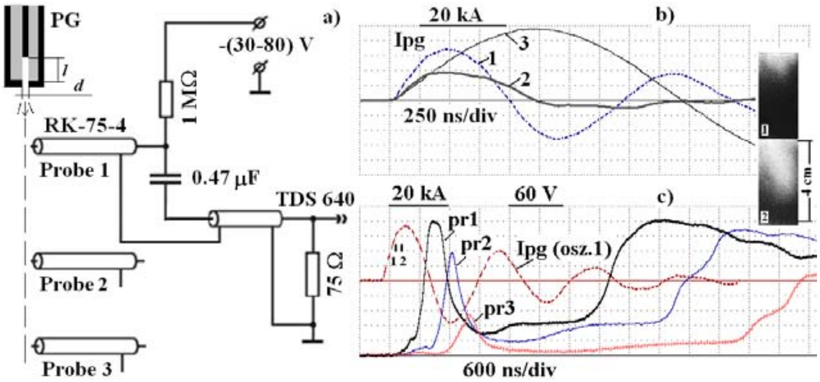

Fig. 1. Probe measurement scheme – a), discharge current forms in PG – b), characteristic signals from probes at Upr = – 60V for current form 1 – c), on the right – frames of 1.2 "Nanogate 2", taken with an exposure of 20 ns at intervals of 180 ns.

In [1], the results of experiments with capillaries made of polyethylene for the rising current edge of ~ 1.2 µs are shown (osc. 3, Fig. 1). In the present work, the results for the rising current edge are ~ 0.4 µs (osc. 1, fig. 1). For capillaries with a length of l = 5, 10, 15 mm c d = 1.5 mm at a constant voltage on the power source Uc = 50 kV for a current of 7.3 kA, the speed of the first bunch (osc. pr1-pr3, fig.1, c) is constant within the measurement error. An increase in current to 13.4 kA leads to a synchronous increase in the average velocity for all lengths from ~ 11 to 13 cm / µs. For l = 15 mm, an increase in the voltage Uc from 40 kV to 55 kV (ΔUc = 5 kV) with an increase in the current in the capillary from 5.9 kA to 8.1 kA leads to a linear increase in the average speed by ~ 1.25 times (from 10 to 12.5 cm / µs). At a current of 10.7 kA (Uc = 40 kV) the speed is ~ 13/5 cm / µs, at a current of 13.4 kA (Uc = 50 kV), v ~ 14.5 cm / µs. Thus, an increase in the current in the capillary by ~ 2.3 times led to an increase in speed by 1.45 times ($v \sim I^{1/2}$). With a current in the capillary of ~ 7.2 kA, the transition from the oscillatory mode with a front of 420 ns (osc. 1, fig. 1, b) to aperiodic with a front of 250 ns (osc. 2, fig. 1, b) did not lead to a significant change in velocity.

For a teflon capillary with copper electrodes (d = 3.5 mm, l = 15 mm, I = 30 kA, τ_f – 420 ns), the main flow has a speed of ~ (4.5-5) cm / µs, a jet opening angle of ~ 20°, $n \sim 10^{15}$ cm^{-3}. For corundum (Al2O3, d = 2.2 mm, l = 5 mm, I = 7.4 kA, τ_f – 420 ns) with Al electrodes when injected from a 2 mm hole with a speed of ~ (4.4-5) cm / µs, using a mixer Laval nozzle type – v ~ (5.8-6.4) cm / µs. In both cases, the amplitude of the blower, having a speed of v ~ 10 cm / µs and a half-height duration of $\tau_{1/2}$ ~ 300 ns, drops sharply after 2-3 operations.

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THE DISTRIBUTION OF PLASMA PARAMETERS ALONG THE AXIS OF THE HOLLOW ANODE IN THE PLASMA ELECTRON EMITTER [*]

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Low pressure discharges (≈ 1 Pa) are used to harden the surface of materials and products in order to increase their lifetime [1]. A non-self-sustained discharge with a hollow cathode with the injection of an electron current of up to tens of amperes makes it possible to achieve a plasma concentration of about 10^{18} cm^{-3} at a pressure of 1 Pa with a radial inhomogeneity of about ± 13% in the volume of the vacuum chamber of ~ 0.2 m^3. The dimensions of vacuum chamber are about 600 × 600 × 600 mm [2].

However, in a system with an extended hollow cathode with a large length-to-diameter ratio of the hollow cathode (> 1.5) with a relatively small area of the output aperture of the emitting electron source, from which electrons are injected into the main glow discharge, an increase of inhomogeneity is noted. Electron injection can be performed not from the emission center of a small area located in the plane of one of the walls of the hollow cathode, but inside the hollow cathode from a relatively large area in order to reduce the inhomogeneity of the glow discharge plasma parameters. As an implementation of this concept, a system with a grid long cylindrical emission electrode was assembled. In this system, the injection of electrons is performed through the emission electrode to the cathode walls, due to which an increasing of the homogeneity can be achieved. The grid long cylindrical emission electrode is the anode of the electron source.

In this paper, plasma generation processes in a hollow long cylindrical grid anode of a non-self-sustained arc discharge with heated and hollow cathodes were investigated. The distributions of plasma parameters of a non-self-sustained low-pressure arc discharge were measured along the axis of the hollow anode. The effect of electron injection into the pulsed main non-self-sustained glow discharge on the parameters of an arc plasma in a hollow anode was determined.

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PROFILE FORMATION OF EMISSION CURRENT OF GRID PLASMA CATHODE IN A LONGITUDINAL MAGNETIC FIELD*

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The design of a gas-discharge system of a plasma grid cathode, designed to work with a pulsed electron source [1] that generates an intense low-energy electron beam transported in a longitudinal magnetic field, has been presented. The two-stage gas-discharge system, which includes the 1,3 initiating and main low-pressure arc discharge electrodes 3,5-8, generating an emission plasma, provides a discharge current of at least 500 A with a current pulse duration of 20-250 μs. An electron source with a presented plasma cathode allows generating a pulsed intensive (with a nominal current of up to 300A and a maximum of up to 500 A) a low-energy (up to 25 keV) electron beam transported in a longitudinal magnetic field of 0.02-0.05 T.

A feature of the gas-discharge system of the plasma cathode is the work in a non-uniform longitudinal magnetic field (5-30 mT), penetrating into it from the beam transport area, which can lead to compression of the discharge. By optimizing the geometry of the electrodes, the location and orientation of additional permanent magnets in the discharge system, a steady initiation and stable operating (without current interruptions) of the main discharge in the working range of the gas pressure (Ar) $(2\text{-}8)\cdot 10^{-2}$ Pa has been achieved. A stable attachment of cathode spots on the Mg-insert surface of the discharge cathode and an axially symmetric discharge current flowing around the redistributing electrode 7 in a longitudinal magnetic field has been observed. Installing an electrode 7 with a large diameter provides an efficient redistribution of the discharge current over the surface of the emission grid 8. The initial distribution of the emission current over the beam section is controlled by changing the conditions of the discharge current flow around the electrode 7, which is achieved by adjusting the magnetic field penetrating the discharge system. When a beam is transported in a magnetic field, the profile of the electron beam changes with the formation of a maximum current density in its central part. By correcting the initial current distribution obtained from the plasma cathode (forming the beam profile close to the ring one), it is possible to eliminate the indicated maximum and to obtain a beam with a diameter of up to ≈ 35 mm with a heterogeneity of ± 10% of the average value.

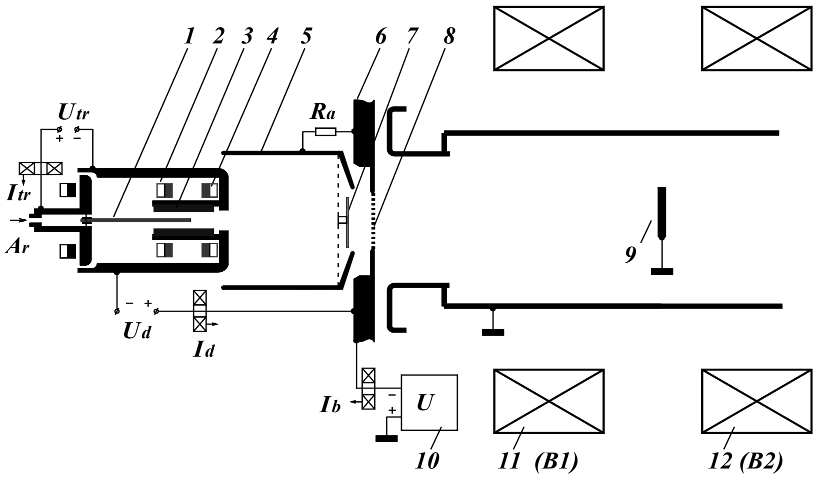

Fig. 1. Experimental setup: *1* – anode of ignition discharge, *2,4* – permanent magnets, *3* – Mg cathodes, *5* – anode insert, *6* – main discharge anode, *7* – redistributive electrode Ø 40 mm, *8* – emission grid window Ø 50 mm, *9* – collector, *10* – high voltage power supply, *11,12* – solenoids. *Utr* – ignition discharge power supply, *Ud* – main discharge power supply.

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THE DEFLECTION OF A WIDE ELECTRON BEAM FROM THE LONGITUDINAL AXIS OF THE SOURCE WITH A PLASMA CATHODE AND PLASMA ANODE*

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The interaction of the electron beam with the target leads to intense gas desorption, evaporation of contaminants from the target surface, to the melting of the target, as well as to ionization of the vapors by the electron beam, forming a collector plasma. These pairs can reach the emission electrode, contaminating its surface, therefore, reduce the electrical strength of the accelerating gap [1]. The presence of a collector plasma leads to the formation of an ion flow, which either charges dielectric inclusions on the grid, or causes a violation of the layer stabilization of the emission plasma boundary, which also reduces the electrical strength of the accelerating gap [2].

To eliminate this problem in this work, it was decided to carry out the deflection of the electron beam from the longitudinal axis of the source. In the experiments, an electron source with a plasma cathode with grid stabilization of the boundary of the emission plasma and a plasma anode, the boundary of which is open, was used. The dotted line circled the developed magnetic system of the electron beam deflection, consisting of solenoids 1-5 and sector tap 6. Solenoids 7, 8 are located on the drift tube for transporting the beam.

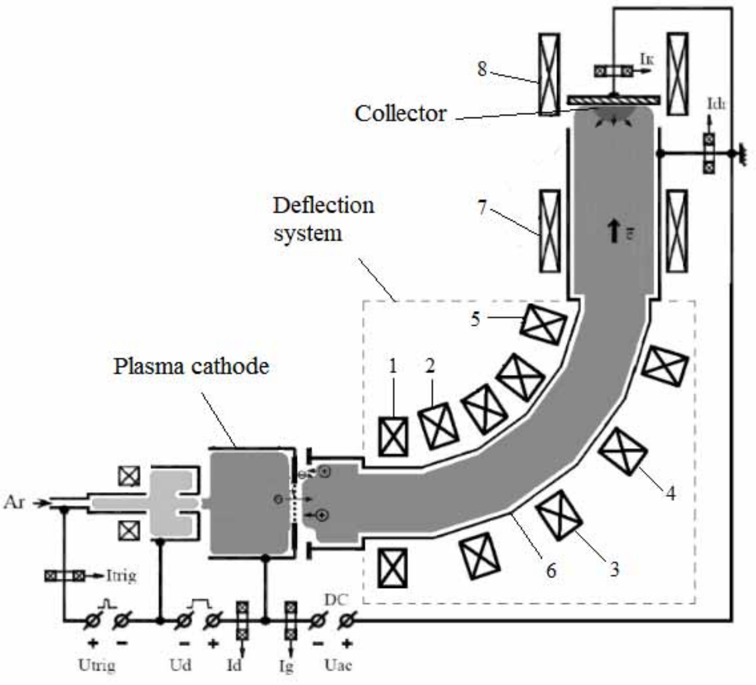

Fig. 1. Scheme of a pulsed beam installation with a plasma cathode

It was experimentally shown that the introduction of an electron beam deflection system into the design of the source described allows an increase in the electrical strength of the accelerating gap up to 6 times, and thereby expand the limiting parameters of the electron beam. It was also found that there are different mechanisms of electrical breakdown of the accelerating gap: the first is associated with the total energy content of the beam, and the other with the violation of the stabilization of the boundary of the emission plasma.

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OPTICAL EMISSION STUDY OF PLASMA VORTEX RINGS AT ATMOSPHERIC PRESSURE AIR*

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Reactive turbulent vortex rings are traditionally of scientific interest, in particular, in the tasks of intensification of combustion processes [1], interaction with flames [2]. It was reported about the formation of plasma vortex rings during the expansion of a pulsed plasma jet in atmospheric air [3]. The optical emission of such structures considerably exceeds the time of the energy deposition. The physical properties of such multiphase vortex flows are generally poorly studied.

The paper presents the results of high-speed optical emission study of plasma vortex rings. The device for generating is similar to described in [3]. The spectrums were recorded using a high-speed CMOS spectrometer with a resolution of 1.5 nm and a frequency of 1400 fps. The emission spectrums in the time interval up to 11 ms after the start of the outflow were registered. Fig.1 shows the recorded spectrums corresponding to 0.725 and 4.60 ms.

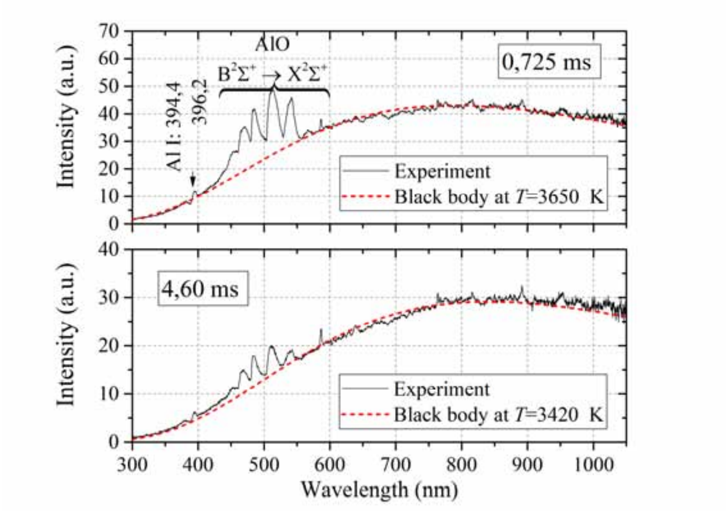

Fig. 1. The emission spectrum of plasma vortex ring

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HIGH-SPEED IMAGING PYROMETRY OF PLASMA VORTEX RINGS AT ATMOSPHERIC PRESSURE AIR*

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Under certain conditions, the pulsed injection of plasma jets into atmospheric air leads to the formation of large-scale vortex plasma structures. Their afterglow time considerably exceeds the energy deposition times [1]. Interest in such formations is largely due to the prospect of creating high-intensity optical radiation open-sources [2]. For the construction of theoretical models of such objects, it is necessary to know their temperature characteristics.

The present study is concerned with investigation of temperature dynamics of plasma vortex rings. A pulsed electrothermal plasma generator based on a localized electrical explosion of wire was used to generate the vortex rings.

Studies were conducted using a developed high-speed imaging pyrometer. The system based on high-speed monochrome camera Videosprint (NPK Videoskan, Russia) and optical filters with transmission maximum wavelength at 475 nm and 16 nm FWHM. The spectral sensitivity is located in the spectral band regions of AlO that makes it possible to detect regions with the most active reactions. Fig. 1 shows the temperature map of the vortex ring in the late stage of its afterglow.

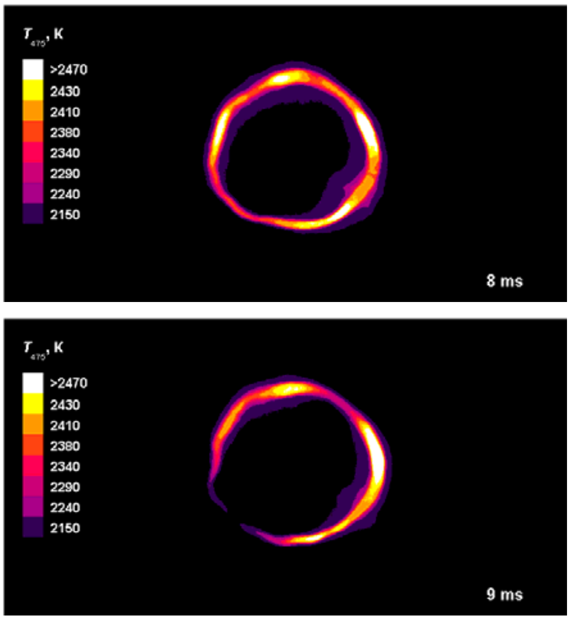

Fig. 1. Spatial temperature map of plasma vortex ring.
Frame size - 0.75 x 0.4 m.

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FOIL LINER IMPLOSIONS WITH A NANOSECOND RISE TIME OF CURRENT THROUGH THE LINER*

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Experiments on implosion of aluminum foil liners with a diameter of up to 2 mm were carried out on the high-current MIG generator (2 MA, 80 ns) with a current rise time through the liner of about 1 ns. To reduce the rise time of the current through the liner to 1-2 ns, the liner area is pre-filled with plasma with ion density of 10^{16} -10^{17} cm^{-3}. Fast current switching to the liner is realized in the process of sweeping the injected plasma by the generator current ($J \times B$ force) in the "snow plow" mode [1]. Since the acceleration time of the liner with the initial radius r_0 to a given velocity v is about $\tau = 3r_0/v$, reducing the rise time of the current through the liner and, therefore, the liner implosion time allows to reduce its radius. The Rayleigh-Taylor (P/T) instability has the most destructive effect on the process of liner implosion. In the linear stage of P/T instability development, the increment of longitudinal perturbations is $\gamma = (kg)^{0.5}$. Here k is the perturbation wave vector; g is the liner acceleration. For a fixed wave vector k, the determining growth of perturbations during the liner acceleration time τ integral $\int\gamma dt \propto \gamma\tau \propto \tau g^{0.5} \propto \tau(v/\tau)^{0.5} \propto \tau^{0.5}$ is proportional to the square root of the liner acceleration time τ to a given velocity v. In addition, it is well known that the most dangerous are perturbations with a wavelength λ close to the thickness of the liner Δ. This is due to the increment increases with decreasing λ, and the perturbations with $\lambda < \Delta$ in the nonlinear stage of their development go into saturation mode. With a constant liner mass per unit of its length $m = 2\pi r_0\Delta\rho$ (ρ is the density of the liner material) its thickness is $\Delta \propto 1/r_0 \propto 1/\tau \propto 1/k$ and in this case $\int\gamma dt \propto \tau$. That is, reducing the time of liner acceleration to a given velocity and a corresponding decrease in its initial radius leads to an increase in the stability of the liner implosion. Note that reducing the initial radius of the liner implies a corresponding decrease in its final radius. This reduction may be, for example, proportional with a fixed degree of the liner radial compression or higher due to a higher degree of the liner radial compression because of the above-mentioned stabilization of the liner implosion.

The paper presents experimental results for shots with 8-µm-thick aluminum foil liners. Liners with initial diameters from 0.65 mm to 2.0 mm were used. With the rise time of the current through the liner 1-2 ns, the implosion time of such liners ranged from 7 ns to 35 ns. Dynamics of the liner Implosion was numerically calculated using a 0-dimensional model and assuming that the current instantaneously switches to the liner at the time of the first radiation peak (associated with the fast explosion of the skin layer on the surface of the liner and the formation of a layer of high-temperature dense plasma [2]). A satisfactory agreement between the experimental and calculated times of liner implosion is noted. This indirectly confirms that the time of the current switching to a 10-mm-long liner does not exceed 2-3 ns.

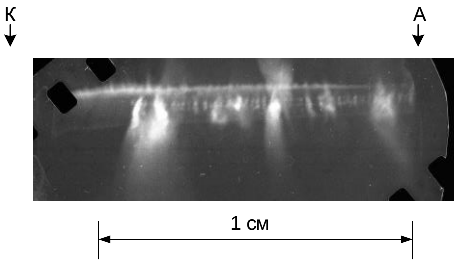

Fig. 1. Side-on time-integrated soft x-ray image for a shot with a 0.65-mm diameter, 8-mm length aluminum liner. The image shows emission from the surface of the liner, and on-axis formed pinch.

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PLASMA SOURCES AND EQUIPMENT

EVAPORATION OF POLYCRYSTALLINE SILICA-ALUMINIUM CATHODE IN CATHODIC ARC VACUUM DISCHARGE

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Introduction. The most widely used technologies of silica and silica containing coating production are the sol-gel, CVD methods, magnetron sputtering in vacuum [1] and ion-beam sputtering. Alternative method for continuously coating is the evaporation with vacuum cathodic arc in arch-like magnetic field (steered arc) [2, 3, 4]. This method provides with high film density, fine film adhesion, high performance without thermal cracks of the cathode. At present vacuum arc discharge on silica cathode in the arch-like magnetic field is studied insufficiently. The report is devoted to the investigation results of the magnetic field influence on the discharge parameters and erosion products composition of the silica-aluminum cathode.

Experiment. The work was carried out with the butt cathodic arc evaporator with cathode diameter 150 mm [2]. The discharge current was from 19 to 25 V, induction magnitude of arch-like magnetic field varied from 0 to 13 mT. The characteristics of macroparticles were investigated within thin films on the substrates placed on 240 mm from the cathode surface with the help of confocal and atomic force (AFM) microscopes.

Results. It was shown that increasing of magnetic field induction from 0 to 13 mT leads to discharge voltage changing from 19 to 25 V. At that tame the cathode spots motion velocity increases from 1.5 to 5 m/s. Further increasing of magnetic field induction leads to the discharge instabilities. Increasing of the spots motion velocity provides with cathode erosion rate decreasing from $5.3\cdot10^{-8}$ to $3.2\cdot10^{-8}$ kg/C (in 1,6 times) (Fig. 1).

The statistical characteristics of the macroparticles on the substrate and in the plasma flow were obtained. It was shown that increasing of the magnetic field induction on the cathode surface decreases particles number on the substrate up to 1.5-2 times. At the same time the decreasing of mass fraction of the particles in the coating from 0.3 to 0.2 takes place (Fig. 2). It was shown that most of macroparticles mass is transferred with the droplets in plasma of 0 to 0.8 um diameter.

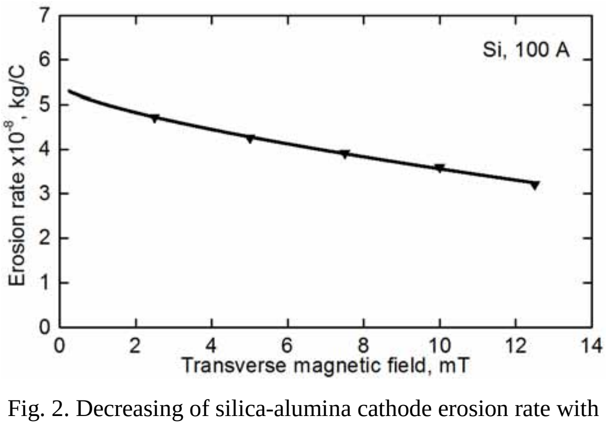

Fig. 2. Decreasing of silica-alumina cathode erosion rate with increasing of magnetic field

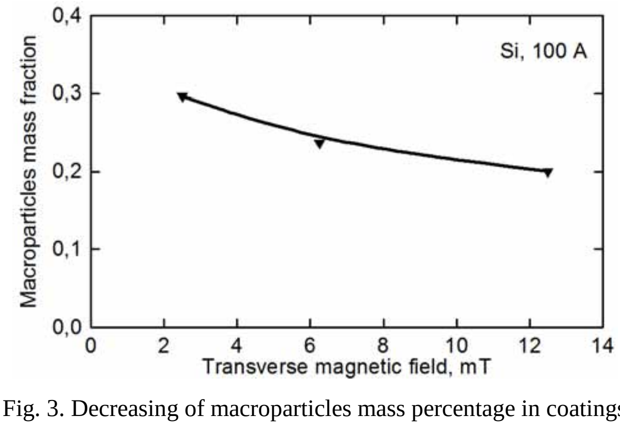

Fig. 3. Decreasing of macroparticles mass percentage in coatings with increasing of magnetic field

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EXPERIENCE OF FORMATION OF COMBINED LOW ENERGY ELECTRON-ION BEAMS IN PLASMA SOURCES OF CHARGED PARTICLES

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One of the methods to increase the efficiency of ion sources used for deposition of thin-film layers of metals, semiconductors and dielectrics is the use of high-current electron emitters to support ionization processes and ensure stable discharge burning, compensation of both the volume charge in the beam, and the surface charge on the formed film. Currently, thermal emitters are used for these purposes [1]. However, under conditions of intense ion fluxes, the resource of such emitters is limited due to intense ion bombardment. Therefore, the search for these purposes of non-termal emitters of electrons is quite relevant. Low-energy electron beams are also of interest for the implementation of plasma-chemical processes and technologies for deposition of films and coatings for various purposes using alternate or simultaneous thermophysical electron and modifying ion effects.

In systems with a plasma emitter, the production of low-energy compensating electron beams is possible either due to energy recovery or by creating optimal conditions for the formation of such beams directly at the source. In the formation of electron beams of the required geometry in systems with a plasma emitter, the position and shape of the emitting plasma surface are decisive. They, in turn, are determined by the plasma parameters, the characteristics of the beam-forming system (the potential and geometry of the forming electrodes), and the magnitude of the reduced field strength accelerating the electrons.

The paper shows the possibility of forming combined electron-ion beams in a single multi-bit structure that does not contain incandescent elements. The design of the electrode structure of an electron-ion source, consisting of two gas-discharge cells of the “Penning” type [2] connected in series (along the axis), is proposed. It is shown that the interrelation of separately controlled discharges in the structure contributes to an increase in the degree of gas ionization under reduced pressure, as well as to the formation of double electric layers in the plasma, ensuring the formation of combined ion-electron flows in a single structure. This is achieved by creating conditions for the electron beam to drift through the entire part of the electrode structure, which ensures the formation of the ion current of the source, and contributes to an increase in the degree of gas ionization in this region. In addition, the deceleration of the electron beam in the gap of ion acceleration ensures the return of electrons that have lost some of their energy to the ionization of the gas to the region of the formation of the ion-emitting plasma. This contributes to an increase in the density of the ion emission current.

The possibility of separate control of the accelerating voltages of electrons and ions in the developed structure provides for regulation in a wide range of ratios of the energies of electrons and ions, as well as the densities of their currents in the electron-ion beam. This expands the range of possible technological application of the electron-ion beam source.

The results of the research indicate the promising application of the developed structure for the design of technological sources of combined electron-ion beams.

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PLASMA SOURCES AND EQUIPMENT

PULSED JETS FOR DENSE PLASMA GENERATION IN AN EXTERNAL MAGNETIC FIELD [1]

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The calculation of pulsed jets of a capillary discharge with an evaporating wall is presented. A plasma source [1-17] based on a plasma jet formed at the end of a capillary discharge at atmospheric pressure is considered.

A mathematical model of a system of pulsed plasma jets flowing into a submerged space, based on the equations of radiation plasma dynamics, written in arbitrary curvilinear coordinates, is developed. Radiation and gasdynamic processes arising in a system of capillary discharges with an evaporating wall, which expire in a submerged space, are numerically investigated. Calculations of all the main gasdynamic and radiative parameters of a capillary discharge system with an evaporating wall are made. A numerical simulation are carried out and spatial distributions of pressure, temperature, velocity and Mach number in a pulsed jet of a capillary discharge and a system of pulsed jets of a capillary discharge with an evaporating wall at different points in time are obtained.

These jets flow from an array of capillary discharges located nearby with an evaporating wall. The interaction of the peripheral parts of pulsed plasma jets emanating from a capillary discharge with an evaporating wall affects external shock waves separating the plasma of each capillary discharge with the evaporating wall from the gaseous medium (air) in the submerged space. In this region, two shock waves collide with a noticeable increase in the values of gasdynamic parameters in the interaction zone (pressure and density increase approximately two times). At the same time, outside the interaction zone (for a given time point), the thermo-gasdynamic parameters of a capillary discharge with an evaporating wall correspond to the values in the plume of a single capillary discharge. Note that all noted phenomena require further detailed and comprehensive study.

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TANDEM ANALYZER OF PLASMA FLOW IONS BY ENERGY, MASS AND CHARGES*

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The main areas of application of ion analyzers for energy, mass and charge are the study of the surface of solids, the study of the structure of matter and the processes of interaction in collisions of particles in gases and plasma, in particular, with the location of the analyzer in the area occupied by the plasma.

In our case, it is proposed to perform energy, mass and charge analysis in a tandem of successively located energy analyzers with retarding potential (RFA) and Wien linear filter (WF), and ion detection is performed on a detector located at the output of the tandem of two analyzers (Fig. 1a). The sequence of analyzers in tandem can be reversed: linear WF – RFA (Fig. 1b).

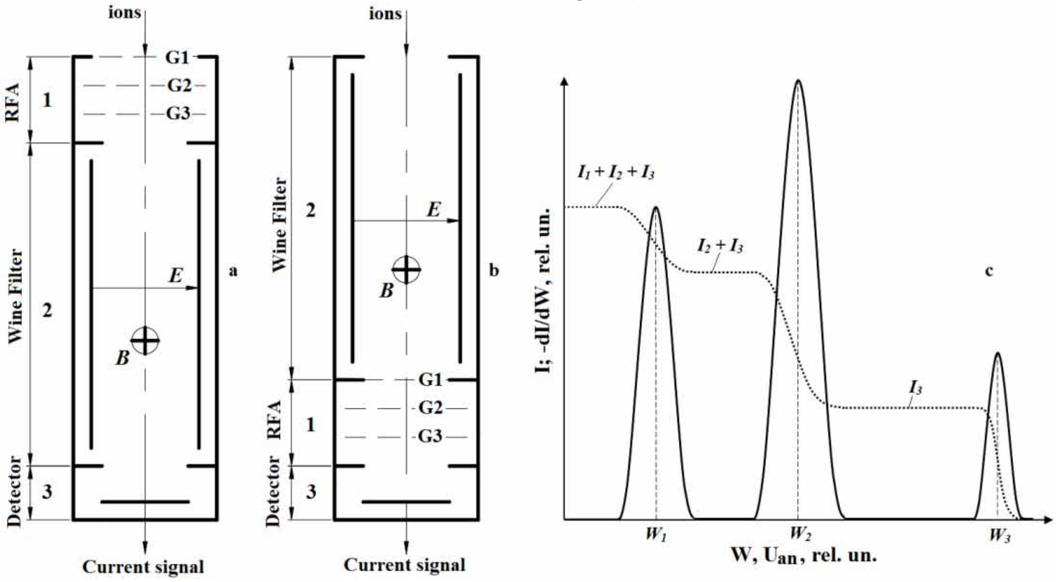

Fig. 1. Tandem analyzer of plasma flow ions by energy, mass and charges: a, b – analyzer options; c – for option Fig. 1a current I of the detector when registering a three-component flux of ions having a wide energy spectrum W with masses m_1, m_2 and m_3 at a fixed setting WF and changing the potential of the analyzing (G3) grid U_{an} RFA from zero to the value $eU_{an.max}$ ensuring locking of all the incident ions flow; $\boldsymbol{E}$ – electric field strength; $\boldsymbol{B}$ – magnetic field induction.

Let there be ions of three masses m_1, m_2, and m_3 in the flow, with $m_1 < m_2 < m_3$. On the detector, the mass ions m_1 will not disappear until the decelerating field of the G3 RFA grid reflects the ions of mass m_1 with energies from the initial minimum $W_{min.1}$ to the tuning energy WF $W_0 + \Delta W$, where ΔW is the energy resolution of WF. On the delay curve $I = f(U_{an})$, the current in these conditions will be defined as $I = I_1 + I_2 + I_3$ (see Fig. 1c). With a further increase in U_{an}, the ions of mass m_1 leave the area of the WF tuning, the signal from these ions disappears. On the delay curve, the amplitude of the current decreases to the level $I = I_1 + I_2$. For even larger values of U_{an}, the contribution from the ions with mass m_2 will disappear and the ion current will be determined only by the current of particles with mass m_3. The current from the detector will become zero at $eU_{an} \geq W_{max.3} + \Delta W$. On the delay curve, the current steps will be visible, the number of which is equal to the number of different masses of the ions in the incident flow – 3 in our case.

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A CALIBRATION METHOD FOR PHOTOELECTRIC RADIATION DETECTORS FOR MEASURING HIGH-INTENSITY PULSED SOURCES

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With the development of high-intensity pulsed radiation sources (RS) such as laser and flash lamps the task of detecting the temporal nature of the radiation power was actualized. In this case the following requirements on radiation detectors are imposed: high temporal resolution (no more than 0.1 of light pulse rise time), long-term stability, reliable calibration technique with a relatively small error.

Pyroelectric sensors with a wide variety of receiving surfaces sensitivity and long-term stability are the most widely used for laser radiation measuring. However, in case of continuous-spectrum flash lamp the broad spectral range of the detected radiation and inconstancy of the spectral sensitivity complicate the interpretation of measurement results.

To study the radiation parameters of continuous lamps, photodiode based radiometers with a built-in integrated amplifier are widely used. Calibration methods for such detectors are simple and have a small error (≈ 5%). The low temporal resolution and absolute sensitivity of the detector, as well as the presence of an integrated amplifier, do not allow the recording of high power short pulses.

On the other hand, photodiodes themselves have a high temporal resolution and the selection of sensitivity for any RS is not a laborious task. A wide choice of the spectral sensitivity ranges makes it easy to personalize a problem solving and to calculate the emissivity of the RS with a relatively small error.

However, the calibration of such detectors is a time-consuming task, requiring a reference high-intensity radiation source with a known spectral distribution. The error of such methods is usually at the level of 15%.

This article describes a method for calibrating a photodiode device for detecting high-intensity radiation pulses using continuous lamps. The method based on using an attachable integrated amplifier with a calculated and confirmed by measurements time constant. Based on the value of the detector's sensitivity (obtained during calibration) and time constant, the correlation coefficient between the radiation power and the photodetector response is mathematically obtained.

This technique was tested on the example of a xenon flash lamp with a half-height pulse duration of ≈ 55 μs.

POWERFUL SOURCE OF VUV-UV RADIATION BASED ON NANOSECOND VOLUMETRIC DISCHARGE

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When applying a high-voltage subnanosecond pulse (< 1 ns) to a coaxial matched low-inductance gas chamber at an air pressure of 1 atm, a powerful volumetric discharge is obtained emitting in the VUV-UV range.

To form a volume discharge, a modernized generator (250 kV) with a pico-nanosecond (0.1–5.0 ns) pulse duration and a current of 5 kA with a pulse repetition rate of 0.1–12.5 Hz is used. This device, like the previous one [1], is made according to the hybrid Tesla generator scheme, where the output circuit capacity is divided and its components C1 and C2 form a two-stage Marx generator. Unlike the device [1], the components C1 and C2 of the Marx generator have a special design and their capacity is adjustable. These capacitors are charged in the first semi-period of the Tesla generator operation. The VUV-UV spectrum and the kinetics of intense flares were measured in the spectral range of 12 – 200 nm using the complex (VMS-1, PEM-142, PEM-31, p-i-n diode FDUK-1UVSKM, Tektronix TDS3032B). The duration of VUV-UV plasma pulses < 1 nc is achieved in air, Ar and He at a pressure of 1.0–1.5 atm. The emission spectrum of emission of a powerful volumetric gas-discharge plasma source has a VUV boundary about 12 nm. A preliminary analysis of the experimental results shows that the spectral maximum of plasma emission lies in the range of ~ 25–30 nm and the surface power density is about 10^7 W/cm^2 at a stored energy of the discharge of 200 mJ.

In the volumetric discharge mode, plasma emission is observed only in the VUV-UV spectral range. A different picture takes place in the development of a streamer mode of the discharge over the nanosecond duration of the generator. In this case, the spectrum of less intense radiation of the plasma is located in the visible range. Such a significant difference in the energy, spectral and kinetic characteristics of the volumetric and streamer discharges is explained by the magnitude of the discharge gas volume. The discharge streamer has a cross-section of 1–3 μm, a large length, but a very small discharge volume. Therefore, the resistance of the streamer channel is significant; the discharge decay time reaches 300 ns and the discharge power drops sharply. Since the radiating volume of the streamer is small, the unexcited volume of gas effectively absorbs the VUV-UV radiation of the streamer and its spectrum is observed only in the visible spectral range. On the contrary, for the case of a volumetric gas discharge, with the same length of the discharge gap, its volume (~2 cm^2) exceeds by eight orders of magnitude the volume of the streamer and occupies the entire active zone of the chamber. In this case, the dynamic resistance of a volume discharge becomes negligibly small, the duration is <1 ns and its power is more than four orders of magnitude higher than the power of the streamer discharge.

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PULSED FIELDS INFLUENCE ON PIG ION SOURCE PERFORMANCE

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Penning ion sources (PIG IS) with self-sustained discharge have some disadvantages particularly expressed in pulsed or frequency regimes. It seems interesting to investigate the possibility of its pulsed magnetic field modulation by appropriate coils with rather large pulsed currents [1]. These fields may trigger the Penning discharge at its initial absence. However, the attempt to simply place an ordinary PIG IS into a solenoid can hardly bring to success due to the field "scinning" and the conductors as well as magnetic materials availability inside the IS [2].

But if instead of coils plane spiral antennas playing roles of PIG IS cathodes are used the difficulties noted above disappear. At that the antenna metal may contact plasma and γ-processes are significant but may also be isolated from it and in this case the discharge excitation occurs only due to the volume ionization (α-processes). Using different types of coils without contact with plasma one may get capacitively coupled plasma (CCP) instead of inductively coupled (ICP) and the decisive role will play just the curl electric field, not magnetic [3]. In fact both are significant but their mutual effect differs in different antennas and currents configurations.

To trigger discharge antennas shown in fig. 1 have been investigated. The estimating fields calculations have been made for antenna (a) at the discharge of the 20 nF capacitor charged to IS anode potential (3 kV) in the RLC contour. Active resistance of this contour R=0.2 Om, its inductivity L=0,5 μH is appreciated with the help of the on-line calculator [4] at the turns number – 8, external diameter – 19.8 mm, wire diameter 1 mm and distance between turns 0.2 mm. Different combinations of the capacitor coupling to the antennas being IS cathodes are examined: both are always at the earth potential (keys – spark-gaps are located between the capacitor and the cathodes); one or both of them are in the initial moment at the anode potential; currents directions during the pulse are the same or opposite. In the later case the pulsed magnetic fields form the monocasp trap. Variants with auxiliary constant magnetic field or without it are investigated.

The calculated pulsed fields – magnetic as well as curl electric one have been used to plasma characteristics estimation according to the method presented in the "plasma module" [2]. These estimations have been made for different hydrogen pressures in the cell of 3 cm length, 2 cm anode height and 60 mT inductivity static magnetic field. This plasma module doesn't allow one to calculate the discharge (anode) current and the extracted ion current determined by ion optics. That's why the presented experimental data for different configurations allow one to appreciate advantages and shortcomings of this PIG IS pulsed performance concept.

Fig. 1. Spiral (a) and twin (b) antennas as well as double spiral antenna.

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PLASMA SOURCES AND EQUIPMENT

*DEVELOPMENT OF ROTATING AMBIENT-AIR ARC JET FOR LOW-TEMPERATURE TREATMENT

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Recently plasma activated water (PAW) is attracting a lot of attention owing to a huge number of possible agriculture and medical applications such as seed germination promotion and disinfection.[1] There are many ways to produce PAW, such as atmospheric pressure plasma jets (APPJ) and dielectric barrier discharge (DBD); however, generation of this type of discharges typically requires expensive high voltage power supply and special gasses (such as He or Ar) to generate the plasma.[2] Turbulent gas flow and small size are making treatment of large targets and powders impossible. Moreover, requirement of special gasses and problems with scaling are limiting conventional DBD APPJ to laboratory studies and research applications. Taking into account problems described above, thermal arc discharges seem to be promising for the development of APPJ considering high density of plasma, wide range of possible parameters of the discharge and possibility of generation of the discharge in ambient air, which allows to perform plasma irradiation using simple experimental setup and reduce treatment costs. Moreover, arc discharge is easily scalable, which could be essential for medical and agricultural applications. However, the high temperatures of ambient-air plasmas lead to serious damages and burning of samples. To overcome the problems, we have developed portable rotating arc generator operated using ambient air flow and investigated the effects of experimental conditions on properties of the discharge and generated in the discharge species.

Arc discharge was generated using high-voltage transformer operated by a push-pull generator, diode rectifier and reservoir capacitor. Discharge gap was organized between rod and ring electrodes by placing tip of the rod electrode to a center of the ring electrode. Ring electrode was surrounded by toroidal magnets for rotation of the arc in the discharge gap. Custom cooling system was developed to prevent heating of the electrodes. Discharges were generated in ambient air with flow rate of air varied in a wide range.

Using the setup described above, it was succeeded to generate rotating arc discharge in ambient air at various flow ratios using small input power (below 50 W). Type of the discharge was changed from spark to low-current arc discharge with increase of input power. Change of type of discharge was clearly observed in the OES spectra and current and voltage waveforms. Discharge parameters and gas flow ratio were tuned to prevent the electrodes heating and keep gas at room temperature after the interaction with the plasma. It was succeeded to generate stable rotating arc discharge at small air flow ratio (0.25-1 slm) and low input power (35W). Low flow rate of air during operation allows to overcome problem with turbulence typically observed in conventional APPJs, which could be essential for treatment of large samples and powders.

Species generated in plasma were analyzed using optical emission spectroscopy (OES) and quadrupole mass spectrometry. Effect of input power and flow rate on the plasma parameters and generation of species were studied and optimized. Rotating arc jet was applied to treatment of water and concentrations of RONS in produced PAW were analyzed using VUV absorption spectroscopy and deconvolution of absorption peaks. It was found, that concentrations of RONS after treatment using ambient-air arc jet was more than 100 times higher than that of PAW produced using conventional APPJs operated with He gas and the same irradiation time.

Construction of the ambient-air rotating arc jet, effect of the experimental condition on concentrations of produced RONs and possible application of rotating arc jet to sterilization of the bacteria will be presented.

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Angular Distributions of Mass and Charge Flow in Plasma Beam Generated High-Voltage Nanosecond Surface Flashover in Vacuum

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In this work we studied the features of angular distributions of plasma flow generated by linear high-voltage nanosecond surface flashover in vacuum. We used the generator with glycerol-filled coaxial forming line. Parameters of the generator are as follows: impedance 25 Ω, stored energy 2 J, voltage 80 kV, voltage pulse duration in match-load mode 30 ns, pulse rise time 2 ns, discharge current 3 kA, current pulse duration 30 ns (first half wave). The samples used were polyethylene (PE), polymethylmethacrylate (PMMA) and polytetrafluorethylene (PTFE).

We measured the distribution of mass flow, density of ions current and ions speed. The distribution of mass flow was measured by the deposition of the flow on thin copper and mica plates. Ion current of plasma flow and ions velocity distribution were measured by the Faraday cup.

We obtained that for all the tested materials the flow of mass as well as the flow of charge are concentrated in thin layer in the equatorial plane (which is normal to the axis of the discharge). The full width of the angular distribution at half maximum is 10 degrees for meridional plane and 60 degrees for equatorial. Also, we observe asymmetry in distribution of ions flow in meridional plane. Probably, the anisotropy of plasma expansion may be caused by the geometry of the current path. In the work we discuss the plasma acceleration mechanisms which may be responsible for these distribution patterns.

POWER SUPPLY FOR OBTAINING THE LOW-TEMPERATURE PLASMA JET*

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In our days, the plasma jets and a plasma sources based on the atmospheric-pressure discharges in the gas flow attract considerable interest not only the researchers but and for the technology and medicine applications [1–7]. The common property for this kind of systems for obtaining the plasma jet is allowing the gas flowing through the discharge gap and a plasma area [1–8]. A wide variety of the electrode configurations, the gases types, and the discharges types are used in the atmospheric-pressure plasma sources [1–8].

The present paper describes results of the investigation of glow discharge burning modes when powered by the high-voltage power supply whit the reactive ballast intended for obtaining low-temperature plasma jet. In the considered system, plasma jet is obtained by using the DC glow-like discharge sustained in the non-steady-state low-current plasmatron with coaxial electrodes. Specialized power supply provides an output voltage up to 6 kV for initiate the discharge, and then realizes discharge current limiting mode. Maximal value of the glow discharge current limited at level about of 140 mA by impedance of inductive-resistive ballast. One of the significant differences of the investigated power supply system from the classical circuit with resistive ballast is the low-frequency modulation of the output voltage, which provides a significant ripple of the discharge current magnitude.

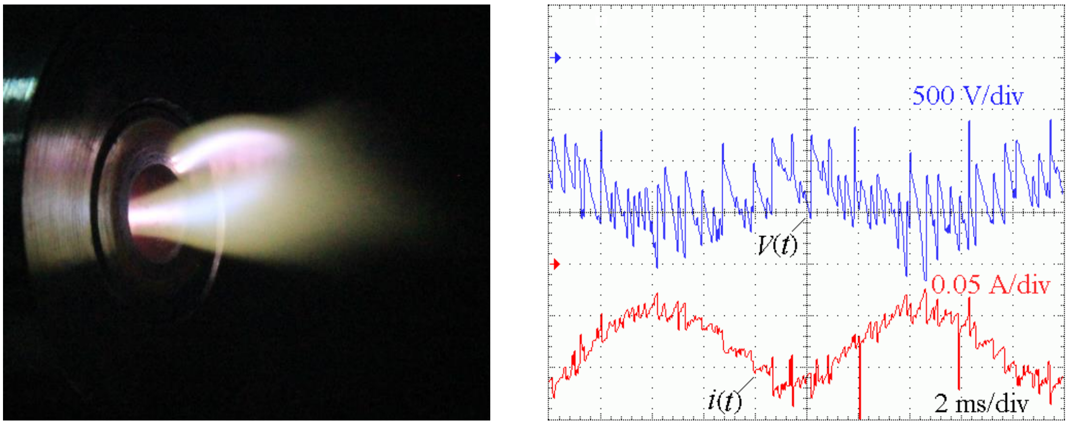

Fig. 1. Photography of plasma jet on the exit of plasmatron nozzle and the glow discharge burning voltage and current waveforms. $V(t)$ – discharge burning voltage, $i(t)$ – discharge current. The gas flow rate G(air) = 0.1 g/s.

Interpretation of the experimental data obtained as a result of the analysis of the waveforms of the discharge current and the discharge burning voltage allows us to reveal the specifics of the DC glow discharge sustaining when powered by the proposed supply system.

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PLASMA SOURCES AND EQUIPMENT

ONE–SEC PLASMA SOURCE FOR FLOW FORMING IN SMOLA DEVICE [1]

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The key problem of plasma confinement in open traps is the suppression of particle and energy losses from the ends. To solve this problem, the concept of screw plasma confinement was proposed [1]. It consists in the creating magnetic plugs moving in the reference system of plasma, whose motion relative to the plasma is created by rotating it in crossed electric and screw magnetic fields. This process is reversible and redirection of plugs movement out of device permits to accelerate the plasma. SMOLA device has been designed and developed for experimental verification of this confinement concept at the BINP SB RAS.

The present work is devoted to the study of the plasma source in the SMOLA device. This axisymmetric system creates a plasma jet by a magnetically insulated discharge with a hot LaB_6 cathode [2]. Using an infrared heater, the cathode is heated to T ~ 2000 K, and the electrons emitted by the cathode ionize and generate plasma with a density of $n \sim 10^{13}\ cm^{-3}$ and T ~ 5 eV at a distance of 0.4 m from the gun anode. To optimize the transport and confinement of the plasma in the trap, it is important to monitor and regulate the primary parameters of the plasma jet. For this purpose, a diagnostic complex has been created. It includes measuring instruments for electrical parameters of discharge, vacuum, as well as power systems control for all high-power circuits.

In this work, the dependences of the plasma jet parameters on the initial conditions of the experiment will be presented, and the influence of the cathode heating, the amount of gas feeding, the amplitude of the cathode voltage on the plasma properties will be assessed.

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SWITCHING DEVICES - EPTRON WITH 100 KV OPERATING VOLTAGE AND A SUB-NANOSECOND SWITCHING TIMES*

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The results of experimental studies of the switching characteristics of the device with subnanosecond switching time, which combines two types of discharges: an open discharge as a plasma source and a capillary discharge which allows fast recovery of electrical resistivity in inter-pulse period and relatively high delay of the breakdown development after applying operating voltage. Two types of capillary structures were tested. First one had a coaxial structure with discharge cross-section 0.16×10 mm^2, assembled from flat circular discs that had 0.16×25 mm hole in the center and separating rings with internal diameter of 10 mm and 20 mm. The total length of the gap was 60mm, the length of separating discs and the capillary structure was 56 mm. Ceramic elements from BeO and ring elements from Al_2O_3 were placed outside the capillary structure in order to prevent outside discharges, this allowed device operation at a voltage up to 110 kV. Unlike [1], the capillary was located at the end of the coaxial kivotron outside. The second capillary structure differs from the first by enlarged slit size of 0.3×10 mm, which made it possible to exclude the effect of runaway electrons from the breakdown process.

Two types of the return conductor were used. First one was a wire conductor with a diameter of 3 mm, removed from the capillary by ~ 40 mm. Second had a coaxial structure with an external conductor diameter of 50 mm. It turned out that for both capillary structures the delay in the development of the breakdown was much greater in the case of the coaxial external conductor, which is associated with the development of a bias current that removes charges from the capillary wall. In other turn, the current-voltage and frequency characteristics of the capillary of the second type were much better. Thus, the working pressure of helium at U = 100 kV for the first capillary was ~ 2 Torr and for the second one equaled ~ 6 Torr. As a result, for the second type of capillary, discharge development delay time remained almost unchanged up to 10 kHz in a burst mode (10 pulses in a burst) with a switching power of 5 kW and up to 2 kHz in the regular pulse mode with a switching power of 1 kW.

PLASMA SOURCES AND EQUIPMENT

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IMPROVING PULSE REPETITION RATE WITH A COMBINATION OF CAPILLARY AND OPEN DISCHARGES*

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Results of experimental studies of the frequency and switching characteristics of devices that combine open discharge, used as a plasma source, and capillary or slit discharge, that provides fast recovery of electrical resistivity in the inter-pulse period, are presented. The difference from the previous work [1] is in the usage of devices with an external placement of capillary or slit discharge sections connected to the part in which open discharge (kivotron) is realized.

Two different device types were investigated. First one was a coaxial construction 50 mm long which consisted from alternate Al_2O_3 rings of 2 types with 8 mm outer diameter and inner of 1 and 5 mm respectively. The other one was a planar construction with a slit that had a cross section of 0.3 mm ×10 mm, assembled from Al_2O_3 plates with dimensions of 40 × 60 mm. In the last case a cooling radiator or a water cooling jacket can be placed directly on the slit wall and at the same time can be used as a return conductor with a minimum inductance of the order of ~ 20 nH.

With a coaxial capillary a planar open discharge cell without the counter propagating electron beams and a coaxial kivotron similar to [1] were used. With a slit construction a planar kivotron with a drift space of 10 mm was used.

It turned out that the removal of the capillary from the inside of the kivotron negatively affects the breakdown development delay and the rate of the electrical strength recovery after a pulse, reducing both parameters by more than an order of magnitude relative to [1]. The main difference between these options is the distribution of the electric field strength during of the voltage raising on the device, which in [1] prevented the straight propagation of electrons to the anode through the capillary, and the breakdown delay time increased. To solve this problem, a casing with the potential of the cathode was put on the outer capillary surface, which one also served as a return conductor with low inductance. In this configuration value of f = 100 kHz with U_a = 30 kV, p_{He} = 3.5 Torr in the case of planar and with p_{He} = 2.6 Torr in the case of coaxial device was achieved.

Device with a slit showed better characteristics than one with a capillary: lower switching time, higher repetition rates, longer delay time, lower residual voltage (≤5% with a the slit and ≤10% with a capillary).

PLASMA SOURCES AND EQUIPMENT

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CREATION OF PLASMA COLUMN TO GENERATE THZ-RADIATION DUE TO ELECTRON BEAM-PLASMA INTERACTION *

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PLASMA SOURCES AND EQUIPMENT

Stable propagation of a kiloampers beam of relativistic electrons (E-beam) in a plasma column and collective deceleration of its electrons at plasma oscillations significantly depends on local plasma parameters. Requirements for plasma parameters are highly controversial. In particular, to form plasma current that ensures beam neutralization both in charge and in current density high plasma conductivity is required. On the other hand, it is necessary to provide an intense beam-plasma interaction at a high level of plasma oscillations that to be transformed into electromagnetic waves going out from plasma to surround space. Nevertheless, such level of plasma oscillations leads to turbulent pulsations of the electromagnetic field in the plasma, accordingly to significant decreasing of plasma conductivity and to breakdown of the current density neutralization for the E-beam. For pumping of plasma oscillations by the beam, it is required suitable plasma density with its acceptable homogeneity. At the same time, to localize the spatial region of maximum beam-plasma interaction on the installation length, one has to create necessary plasma density distribution along the axis of the column. In addition, for the effective transformation of the upper-hybrid oscillations pumped by the E-beam into electromagnetic waves, a plasma density gradient with a strictly specified angle with respect to magnetic field lines is required. We have constructed and are using the system for creation of the plasma column to carry out beam-plasma experiments at GOL-PET facility with taking into account the pointed circumstances. One has to mention at this activity we applied experience accumulated at the creation and operation of GOL-3 and GOL-3T facilities [1].

A high voltage discharge system to create the plasma column at the GOL-PET facility has the following structure. A vacuum chamber made of stainless steel is placed in a magnetic solenoid. The solenoid generates a magnetic field with induction that can be varied up to 4 T. The total length of the vacuum chamber is 300 cm and it is pumped out through its ends. At one end of the chamber, on the side of E-beam injection into the plasma, a quartz tube of 70 mm inner diameter with graphite diaphragms bounding the plasma column in diameter of 50 mm is installed inside the chamber. At the end of the quartz tube, where the E-beam is injected into plasma through a magnetic mirror with an induction up to 7 T, a dense cloud of krypton is fed by a pulse valve. This cloud serves as the cathode of a high-voltage (20kV) discharge. An anode electrode of a high-voltage discharge, which consists of two electrically insulated half-rings, is installed in the middle part of the quartz tube at 40 cm distance of from the point of beam entry. The inner diameter of the half-rings is the same as the inner diameter of quartz diaphragms. A high voltage pulse is supplied on these half-rings independently of each other. It allows creating a different distribution of the discharge current over the cross section of the column and thereby varying the plasma density distribution over its cross section with a diameter of 6 cm. Pulsed feeding by hydrogen into the chamber is carried out by pulse valves installed in its various sections along the length. By varying the delay between starting the discharge current and the moment of fast valves opening, one can obtain various configuration of the plasma density distribution along the length and the cross section of the plasma column. In providing experiments, we measure the current in the coils of the magnetic field and the currents flowing through the anodic semi-rings and through the plasma column in the vacuum chamber. During the discharge current with a duration of 10 μs, fast cameras recorded the optical glow that goes along the axis and across the plasma column. The plasma density distribution of the plasma column at eight points along its diameter was measured by 1.03 μm laser radiation scattering. Integral density value over the plasma column diameter is measured using an interferometer at a wavelength of 10.3 μm. Thus, in the course of experimental studies, various variants of plasma density distribution were obtained. The results of these studies are described in the present report.

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HIGH-CURRENT PULSE NON-SELF-SUSTAINED GLOW DISCHARGE WITH CURRENT UP TO 1 KA [1]

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In the pulsed combustion mode of a non-self-sustained glow discharge with a hollow cathode, the plasma concentration of about 10^{18} cm^{-3} at a pressure of about 1 Pa in the volume of the vacuum chamber ~ 0.2 m^3 was achieved while injecting an electron current of up to several tens of amperes [1]. The degree of plasma ionization in this case is about 1 %. Plasma with a higher degree of ionization is of considerable scientific and practical interest for the formation of electron beams of submillisecond duration with increased (tens of A/cm^2) and ion-plasma product treatment in chambers of large vacuum volumes (>0.1 m^3).

In this paper, the modes of plasma formation in a pulsed non-self-sustained glow discharge with a hollow cathode of about 0.2 m^3 with currents up to 1 kA at a current of injected electrons up to 200 A were investigated. As a result of the probe measurements of plasma parameters, their value in the center of the hollow cathode was obtained and the degree of plasma ionization was calculated.

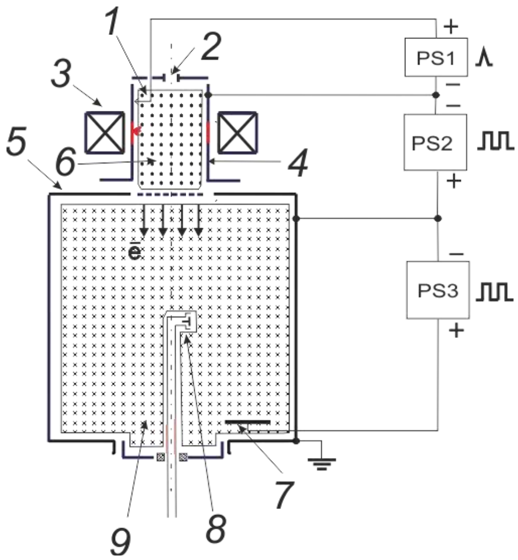

Fig. 1. The scheme of experimental installation. 1 - trigger, 2 – gas input, 3 – magnetic field coil, 4 – hollow cathode of auxiliary arc discharge, 5 – hollow cathode of main glow discharge, 6 – plasma of auxiliary arc discharge, 7 – anode of glow discharge, 8 – plane probe, 9 – plasma of glow discharge, PS1 – trigger power supply; PS2 – arc discharge power supply; PS3 – glow discharge power supply.

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SMALL ANODE DISCHARGE ION SOURCE

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Ion source modification is proposed for efficient production of ion beam and extending of operating Lifetime [1,2]. Ionization efficiency of the Bernas type ion source has been improved by using a small anode-thin rod, oriented along the magnetic field. The transverse electric field of small anode transport plasma by drift in crossed field to the emission slit. Optimization of the cathode material recycling is used to increase the operating lifetime. Optimization of the wall potential is used for suppression of flakes formation. A three-electrode extraction system was optimized for low energy beam production and efficient space charge neutralization. An ion beam with emission current density up to 60 mA/cm2 has been extracted from discharge in BF3 gas. Ion beams of ^{11}B isotope with intensity up to 6 mA for 3 keV, up to 11 mA for 5 keV, 18 mA for 15 keV have been transported through the analyzer magnet. Design of SAS ion source is shown in Fig. 1. Dependence of ^{11}B current on the discharge current for small anode ion source and for Bernas are presented in Fig. 2. Close solution is proposed in [3].

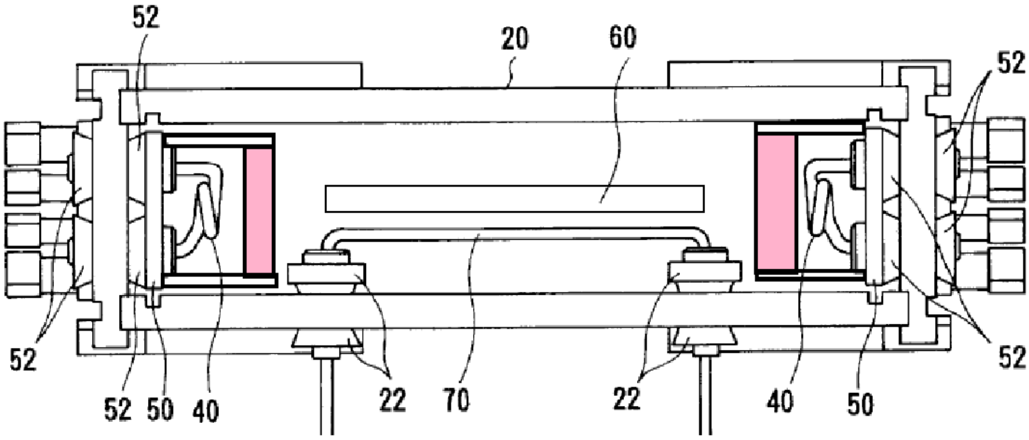

Fig. 1. Design of SAS ion source

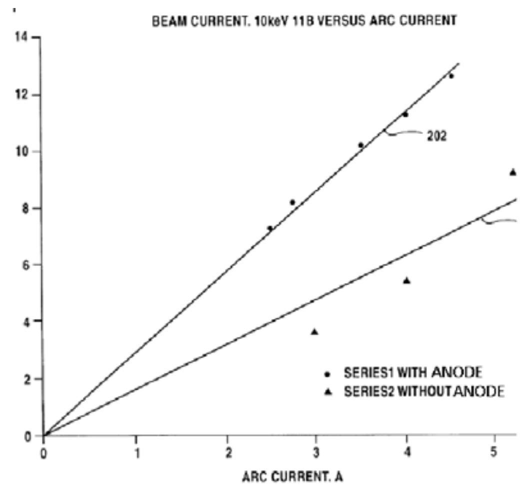

Fig. 2. Dependence of ^{11}B current on the discharge current for small anode ion source and for Bernas type ion source

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PLASMA-PROCESSING REACTOR FOR THE PRODUCTION AND TREATMENT OF NANOSCALE STRUCTURES FOR NANOELECTRONICS

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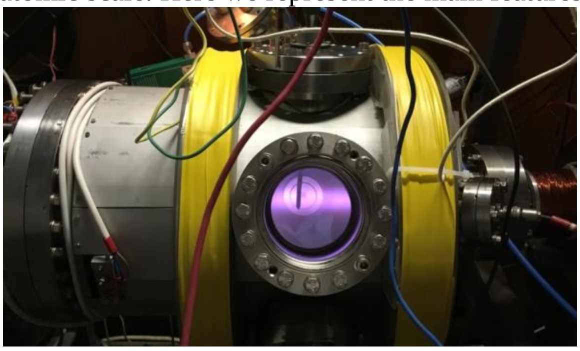
In the production of a wide range of semiconductor devices, from lasers to microwave chips, based on silicon and semiconductor compounds AIII/BV, various plasma chemical processes are widely used for etching and cleaning the surface of semiconductors, dielectrics and metals, and for the thin films deposition on the surface of semiconductor structures. For the treatment of nanoscale materials and structures in nanoelectronic processes it is important to provide "soft", defect-free etching of open surface of structures. Plasma technologies are mainly used RF and microwave discharges for semiconductor devices. Usually the energy of the ions in these discharges is difficult to control.

The work aimed on the creation of plasmas for plasma processing reactors by an electron beam is already known, for example, LAPPS [1]. It is shown that these systems are effective for the creation of plasmas with any gas composition and also capable for creating high density plasmas with cold electrons ($T_e < 0.5$ eV). A low density electron beam (1 - 10 mA/cm^2) is used to form "quiet" plasma by collisional ionization by beam electrons with gas molecules. There are no intrinsic mechanisms of acceleration of ions or plasma in this system. A medium pressure is needed to obtain sufficient ionization, thus the ion flow is influenced by collisions and directivity of the ion flow is too low.

The beam-plasma discharge (BPD) [2-3] used in the plasma processing reactor has several essential advantages [4-9] compared to widely used RF and microwave discharges lower operating pressure, which contribute higher anisotropy of the ion flux on the treated surface; low etching rate and fine control of the average ion energy (in range of 10 - 100 eV) provide treatment with minimum density of radiation defects at atomic scale. Here we represent the main features of the plasma facility based on the BPD (shown in Fig. 1).



Working gases	H_2, D_2, Ar, He, N_2
Magnetic field	Up to 30 mT at the center (Helmholtz coils)
Residual pressure	10^{-4} Pa
Working pressure	$(10^{-3} – 1)$ Pa
Power of the electron gun	up to 2 kW
Plasma density	up to $5x10^{18}$ m^{-3} – Ar plasma up to 10^{18} m^{-3} – H_2 plasma
Electron temperature	up to 10 eV
Ion flux	up to 10^{u} m^{-2}c^{-1}

Fig. 1. View and parameters of the BPD facility.

Also the possibility of ion energy control is studied. The capability of the creation of a plasma reactor which satisfy the technological requirements for low energy etching of semiconducting materials is demonstrated.

This work was supported by the Russian Foundation for Basic Research (project no. 18-38-00884).

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FOREVACUUM PLASMA SOURCE OF RIBBON ELECTRON BEAM WITH A MULTI-APERTURE EXTRACTION SYSTEM

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Electron beams of large cross-section, in particular, a beam of ribbon configuration are used for irradiation of large surfaces and the creation of a beam plasma of significant volumes, and interest in this subject continues to grow. Electron-beam plasma is used for etching, deposition and surface treatment [1]. For the technology of plasma processing of materials, an increase in the plasma concentration, an increase in the volume and homogeneity of the plasma formation, an increase in the possibility of controlling its parameters is required. To solve such problems, reliable and durable electron-beam plasma generators with stable parameters are required. One of the promising beam plasma generators is a forvacuum plasma source that generates an electron beam of a ribbon configuration. Despite the obvious progress in this direction, the problems of increasing the current density of the electron beam of the belt configuration in the absence of a transporting magnetic field, as well as increasing the homogeneity of the electron beam remain open. This paper presents the results of experiments to increase the current density extracted from an extended hollow cathode of a forvacuum electron source. The main feature of the work is the use of a multi-aperture extraction system and the absence of a magnetic field for focusing the ribbon electron beam of the emission electrode in the electron source with a plasma cathode. The optimal geometry of the multi-aperture system is found, which provides an increase in the beam current density while maintaining a high degree of its homogeneity.

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INFLUENCE OF THE SPACE CHARGE OF AN ION BEAM ON THE TIME-OF-FLIGHT DIAGNOSTICS OF ITS COMPOSITION*

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The results of the time-of-flight diagnostics of the composition of high-intensity pulsed ion beams containing protons and heavy ions are presented. The experiments were performed on two types of ion diodes: an ion diode of focusing (see Fig. 1) and planar geometry in the mode of self-magnetic insulation of electrons (250-300 kV, 120 ns, 20-300 A/cm^2) and a focusing diode with external magnetic insulation (300 kV, 80 ns, 100-200 A/cm^2). We used a collimated Faraday cup with magnetic cut-off co-moving electrons as a recording device for ions, time resolution of which is one ns [1].

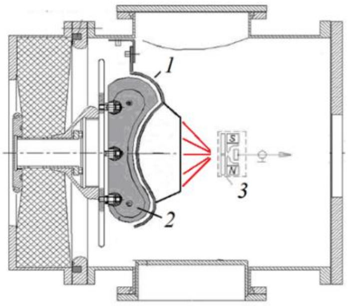

Fig. 1. Schematic of a diode chamber with a focusing diode (1 - cathode; 2 - anode; 3 - Faraday cup)

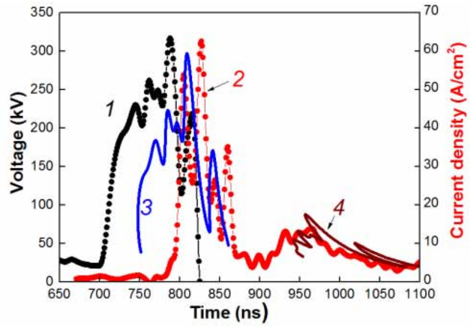

Fig. 2. Waveforms of accelerating voltage, second pulse (1); ion current density in the focus (2, points). Calculated current density of protons (3) and ions Cu^+ (4)

The time-of-flight diagnostics of pulsed ion beams, containing light ions (protons or deuterons [2]) and heavy ions (C^+ or Cu^+, N^+) showed a time delay in the experimental data of the light ions registration by the Faraday cup compared with the calculated values [1]. For an ion beam formed by a diode with planar and focusing geometry in the mode of self-magnetic insulation of electrons, the delay was 40-50 ns on the drift path of 14-16 cm with the ion energy of 250-300 keV. For an ion beam formed by a focusing diode in the mode of external magnetic insulation of electrons, the delay was 10–15 ns (on the drift path of 14 cm at the ion energy of 300 keV) and 16 ns (at the ion energy of 1 MeV on the drift path of 45 cm) [2]. Heavy ions are recorded by collimated Faraday cup before that predicted by calculation (see Fig. 2). With a low proton concentration, the delay in registration of heavy ions does not exceed the measurement error of the time-of-flight diagnostic.

It was shown that the delay of protons registration can be attributed to deceleration of light ions by a negative ion beam space charge during the transport from the diode to the collimated Faraday cup. In the studied ion diodes, the pulse duration of the accelerating voltage does not exceed 120 ns, and in ion beam drift path (10–16 cm) the total spatial separation of protons and heavy ions due to the difference in ion drift velocity occurred. The neutralization of the positive ions space charge by low-energy electrons is necessary condition for its efficient transport and focusing. Our studies have shown that low-energy electrons do not compensate the positive charge of the protons in the front of beam. However low-energy electrons compensate the positive charge of heavy ions; the concentration of the electrons is 1.3-1.5 times higher than that of ions, the total charge is negative. In the absence of an excess concentration of electrons in the ion beam, the delay in the registration of protons is absent. The effect of spatial compression of the ion beam in the direction of the drift increases its pulse power, but complicates the time-of-flight diagnostics of its composition.

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FILAMENTATION OF CURRENT-CARRYING PLASMA SHELLS *

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One of the most effective ways to obtain dense high-temperature plasma is the electromagnetic compression of a matter under the action of a current flowing through the matter. Various types of magnetohydrodynamic instabilities develop in a plasma with current, one of which is the filaments - separate current channels. It is assumed that the filaments result from the development of thermal instabilities, whose growth is determined by the nature of the dependence of the electrical conductivity on the thermodynamic parameters of the substance. If the conductivity increases with temperature, as it happens in plasma, the thermal instability should lead to the appearance of separate current channels [1]. In this paper, we analyzed the development of thermal instabilities in the process of plasma liners compression. Analysis of the growth of instabilities was based on the methods of the theory of small perturbations. The results of this theory were compared with the results of experiments [2] conducted on an IMRI-5 installation (current amplitude 450 kA, current rise time 500 ns).

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PLASMA SOURCES AND EQUIPMENT

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PLASMA SOURCES AND EQUIPMENT

HOLLOW CATHODE PLASMA SOURCE BASED ON RING-SHAPED ANODE LAYER THRUSTER FOR PLASMA-OPTIC APPLICATIONS *

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The conceptual design of plasma source for plasma-optic application and materials modification are investigated. The source presented in this publication are based on plasma thruster’s technology, that were developed by Prof. Goncharov group in Institute of Physics (Kiev, Ukraine) [1]. A specific feature of the presented plasma source is the relatively low magnetic field compared to conventional thrusters. As in the conventional anode-layer thrusters, there are two operational modes of discharge. The first mode is low current with narrow anode layer and clear-cut plasma flow, whereas the second mode operates with high current and plasma fills the entire volume of the hollow cathode. In low-current mode of the source operation, the axially converged ion beam are formed and, as follow from experiment, the energy of the ions could reach some kV. This operational mode can be used for argon or oxygen plasma cleaning as well as coating of outer pipe wall and cylindrical pieces.

The transition to the high-current mode occurs under variation of worked gas pressure and applied voltage. In high-current quasi-neutral plasma mode of operation, plasma jet is observed along system axis. This mode of the plasma source is suitable in a wide-aperture plasma optical system for the electron beam transporting [2].

For effective operation of devices, it is important to know their usage parameters, therefore the electrical characteristics of the discharge operated in different modes as well as the temporal evolution of the pulse current–voltage relations were studied in the feed rate of operating gasses (argon and nitrogen) range up to 20 sccm. The spatial distributions of plasma density and electron temperature of the high-current discharge mode were measured by using double Langmuir probe techniques. Electron temperature did not exceed 6 eV on hollow cathode’s axis, and increased up to 7.5 eV in the vicinity of the anode. The maximum value of plasma density along the hollow cathode's centerline was 2×10^{12} 1/cm^3 for 5 A discharge current. Using a special collector, the measurements of the distribution in the plasma jet flowing along the axis of the hollow cathode were performed. The plasma jet is rather uniform over its cross-section.

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DEUTERIUM ION BEAM FORMATION AND ACCELERATION SYSTEM BASED ON A VACUUM ARC DISCHARGE WITH A GAS-SATURATED DEUTERATED CATHODE*

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Experimental studies on the formation and acceleration of deuterium ion beams using a vacuum arc with a zirconium cathode saturated by deuterium are presented. These experiments are a continuation of our earlier studies, in which we studied the mass-charge distribution of such a plasma with the aim of obtaining the maximum possible fraction of deuterium ions in it [1], investigated the angular and energy distributions of ions [2].

New experiments were carried out using a vacuum arc ion source MevvaV.Ru [3], in which a multi-aperture system for forming an ion beam was replaced with a string ion-optical system. Using a string ion-optical system instead of a multi-aperture one is more efficient in selecting ions from the discharge plasma in the string system, which made it possible to increase the total beam current of multiply charged ions, and, accordingly, the number of deuterium ions generated with the same discharge parameters. In addition, the use of a string system allows to improve the pumping of the anode cavity of the source, which ensures the reduction of impurity ions of the residual atmosphere in the ion beam.

Volt-ampere and emission characteristics of an ion source with a string ion-optical system with zirconium cathode saturated by deuterium were investigated, the radial distribution of the ion current density over the beam cross section was measured. These characteristics are compared with those obtained for a multi-aperture ion-optical system. It was shown that the divergence of the ion beam at an accelerating voltage of 30 kV was about ± 120 mrad, and as the accelerating voltage increased to 60 kV, the beam divergence decreased to values of ± 90 mrad. In this case, the total pulsed current of the ion beam reached values of 1.2 A and more. Earlier [1], we showed that even with a fraction of 40% deuterium atoms in the cathode, the fraction of deuterium ions in the vacuum arc plasma can reach more than 80%. On this basis, and taking into account that the average charge state of zirconium ions in the vacuum arc plasma is 2.5, it can be estimated that the total current of deuterium ions in a pulse can reach values of 0.7 A and more.

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EFFECT OF THE OUTER PLASMA SHELL ON THE FORMATION OF THE CURRENT SHEET IN THE Z-PINCH GAS-DISCHARGE PLASMA*

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Studies of the effect of the outer plasma shell on the formation of the current sheet in a Z-pinch plasma were carried out on the GIT-12 generator (4.7 MA, 1.7 μs) in the IHCE SB RAS, Tomsk. The experimental load was composed of neon, argon or deuterium gas puff surrounded by an outer plasma shell. The outer plasma shell consisting of hydrogen and carbon ions was formed by 48 plasma guns at the diameter of 350 mm. The main idea of using an outer plasma shell is to form a homogeneous, uniformly conducting layer at the beginning of the high current discharge to minimize the amount of matter not involved in the implosion process, and decrease current losses during implosion. Three single-turn B-dot probes, located at the different distances from the Z-pinch axis, gave us the information about the properties of the current sheet and its implosion dynamics. In the optical spectral range, the implosion dynamics was recorded with the help of a streak camera and a frame camera. The experimental data were compared with the motion of the center of the current sheet, obtained from the calculation of the dynamic inductance of the Z-pinch using electrophysical measurements of voltage and current. The optimization of the outer plasma shell injection parameters into the interelectrode gap by the K-shell radiation yield for argon and neon and the neutron yield for deuterium was carried out and compared with experiments without using an outer plasma shell.

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FORMATION OF PULSED LARGE-RADIUS ELECTRON BEAM IN THE FOREVACUUM PRESSURE RANGE BY A PLASMA-CATHODE SOURCE BASED ON ARC DISCHARGE*

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Wide industrial application of ceramics and polymers, which commonly do not conduct electrical current under normal conditions [1, 2], i.e. are dielectrics, requires development of new methods of dielectric materials` treatment. In particular, different methods of surface modification of ceramic and polymer materials are developed [3–5]. The forevacuum plasma-cathode sources of pulsed electron beams, operating in pressure range of 3–30 Pa [6, 7], provide surface modification of dielectric materials due to neutralization of negative charge on the dielectric surface by ions from beam-produced plasma, and by the non-self-maintained discharge between charged surface of the dielectric and grounded parts of a vacuum chamber [8]. Moreover, beam-produced plasma and ion flow from this plasma may also be used for surface treatment. For surface modification of high temperature materials, realization of modification by few (1–10) beam pulses, and some other application of beam, it is necessary to increase electron beam energy in pulse. In the forevacuum pressure range, increase of emission current (current density) and accelerating voltage are limited by breakdown of accelerating gap. Another way to achieve necessary beam energy in pulse is to increase pulse duration up to several milliseconds.

We have used an arc discharge with cathode spot (cathodic arc) for generation of emission plasma with millisecond pulse duration in the forevacuum plasma-cathode electron source. The cathode used in our experiments was made of copper and had diameter of 6 mm. To provide formation of large-radius electron beam, we have used a hollow anode made of stainless steel with height of 100 mm and diameter of 110 mm, and a redistribution electrode mounted inside the hollow anode. The emission plasma boundary has been stabilized by stainless steel fine mesh (emission electrode). The emission electrode and the mesh extractor have formed the accelerating gap. DC accelerating voltage up to 10–11 kV has been used to extract electrons from emission plasma and to form electron beam. Arc discharge current was up to 40 A at pulse duration of up to 10 ms. Influence of the redistributing electrode on the formation of emission plasma has been investigated. Influence of the redistributing electrode, geometry of emission electrode and extractor on electron beam formation in the forevacuum pressure range has been demonstrated.

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GENERATION OF FOCUSED HIGH-CURRENT ELECTRON BEAM WITH MILLISECOND PULSE DURATION BY A FOREVACUUM PLASMA-CATHODE ELECTRON SOURCE BASED ON CATHODIC ARC*

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PLASMA SOURCES AND EQUIPMENT

Pulsed forevacuum plasma-cathode sources generate low-energy (usually no more than 15 keV) large-radius electron beams in the pressure range of 3–30 Pa [1, 2]. These sources provide direct surface processing of dielectric materials (ceramics and polymers) due to neutralization of negative charge on the treating dielectric surface by ion flow from beam-produced plasma and by the non-self-maintained discharge between charged surface and grounded parts of a vacuum chamber [3]. The pulsed large-radius electron beams are usually used for modification of relatively large areas, but there are applications dealing with local treatment of dielectric materials (local surface cleaning, local material evaporation, etc.). Currently, abrasive tools and laser beams are usually used for local treatment of dielectric materials [4–6]. Alternative method of local treatment of dielectrics may be realized by using focused low-energy pulsed electron beam generated in the forevacuum pressure range. In this case, for evaporation of high-temperature dielectrics (ceramics), high energy density per pulse of electron beam is required. Increase of the beam energy density per pulse may be provided by increase of electron beam current density and by increase of pulse duration.

Decrease of electron emission area to several millimeters has provided to generate focused electron beams with beam current up to 3–4 A in the forevacuum pressure range, but pulse duration has not exceed 300 μs, and operation gas pressure has not exceed 5 Pa due to breakdown of accelerating gap. Therefore, to increase the beam energy density per pulse we have used approach based on emission of electrons from relatively large area of plasma, stabilized by mesh electrode (the used radius of emission hole was up to 45 mm), and focusing of electron beam by magnetic field created by two coils. In the experiments, DC accelerating voltage was up to 10–11 kV, the beam current was up to 20 A at pulse duration of up to 5 ms. We have researched influence of geometry of the accelerating gap, magnetic field, gas pressure and gas type on generation of the focused electron beam in the forevacuum pressure range.

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DEVELOPMENT OF THREE-DIMENSIONAL SIMULATION OF DISCHARGE BREAKDOWN

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The phenomenon of electrical breakdown was studied using three-dimensional Particle-in-cell (PIC) code combined with Monte-Carlo simulated gas kinetics . This method has been used to analyze the basic properties of a dc glow and Penning discharges. Our model was verified on calculations of breakdown parameters for hydrogen Penning discharge and alumina vapor breakdown in vacuum. The simulation also shows the importance of three dimensional discharge modeling in transient regimes.

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PLASMA SOURCES AND EQUIPMENT

THE MOTION OF THE PLASMA FLOW IN THE INTERELECTRODE GAP OF THE MAGNETICALLY INSULATED TRANSMISSION LINE*

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The implementation of the crowbar mode in a magnetically insulated transmission line (MITL) with the help of a plasma switch [1] is associated with the propagation of a plasma flow of a planar configuration in a transverse inhomogeneous magnetic field. The paper presents the results of an experiment on the injection of plasma bunches formed by a discharge in a dielectric capillary (see the proceedings of this conference) into the MITL interelectrode gap. Plasma was injected from an external ground electrode onto a central cathode electrode across a linearly increasing magnetic field. The dynamics of the plasma motion was recorded by the "Nanogate Frame-9" two-frame electron-optical complex with an exposure time of 20 ns. The moment of plasma bridging the interelectrode gap was recorded by changing the value of $L_t = U(t)/ (dI/dt)$ according to the method described in [1] and two collimated Faraday cup placed inside the central electrode with an interval of 5 cm in radius. The change of the magnetic field magnitude at the time of the start of plasma injection was achieved by delaying the operation of plasma guns relative to the start of current in the MITL.

In fig. 1 shows the characteristic information obtained in a separate shot. Plasma guns with discharge in a polyethylene capillary (d = 1.5 mm, l = 10, 15 mm) with current Ipg = 7.4 kA (plasma bunch velocity without electromagnetic field $v1$ ~ 11 cm / μs) or Ipg = 13.4 kA ($v2$ ~ 13 cm / μs) and rise time 420 ns injected plasma into the crossed electromagnetic field of the MITL gap. The experiments were carried out for two operating modes of the MITL: mode 1 – $dB / dt \sim 5\cdot10^5$ T/s and the average cathode potential ~ 6 kV, mode 2 - at dB / dt ~ 8.2·105 T/s and cathode potential ~ 12 kV. The average bridging velocity of the MITL gap was taken as $v_k = \Delta_{\text{A-C}} / t_k$ ($\Delta_{\text{A-C}}$ = 4 cm), and B was taken as the average value $B = (\overline{B^2})^{1/2}$ during time t_k. In mode 1 of the MITL for $v1$, with increasing B from 0.27 T to ~ 0.6 T, the speed v_k decrease from 7.5 cm / μs to 4.7 cm / μs. For $v2$, with an increase in B from 0.25 T to ~ 0.7 T, the speed v_k decrease from 8 cm / μs to 4.3 cm / μs almost linearly. In mode 2 of the MITL for $v2$ with increasing B from 0.54 T to ~ 0.9 T, the velocity v_k fell from 5.6 cm / μs to ~ 4.6 cm / μs. Optical diagnostics recorded an increase in the rate of penetration of plasma jets when moving to the cathode 1.2–1.3 times.

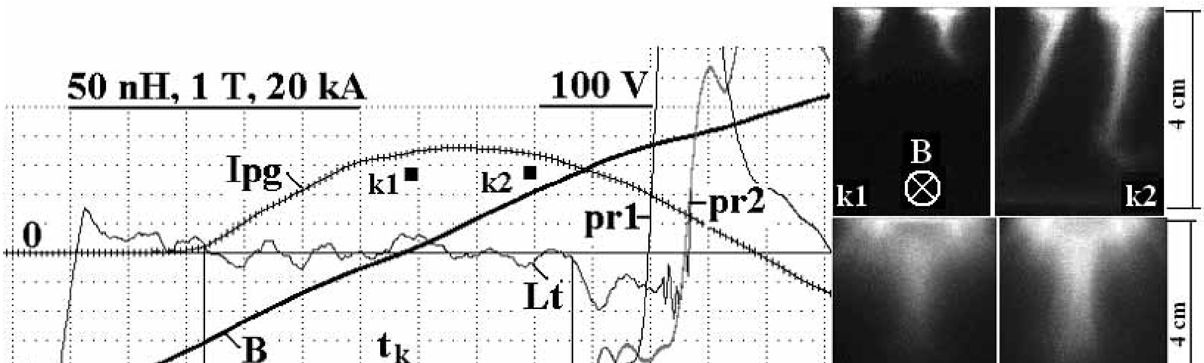

Fig. 1. Current waveform in the capillary *Ipg*, characteristic of the magnetic field in the gap *B(t)*, *Lt* value, signals from the Faraday cup pr1 and pr2, t_k – switching time of the interelectrode gap, squares k1 and k2 – frame timing "Nanogate 2". On the right, there are k1, k2 "Nanogate 2" frames, taken with an exposure of 20 ns and an interval of 200 ns, (k3, k4 – frames with "Nanogate 2" under similar conditions when changing the direction of the magnetic field).

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THE MAIN PLASMA'S PARAMETERS OF A VACUUM INSTALLATION BASED ON LOW-PRESSURE VACUUM-ARC AND MAGNETRON DISCHARGES*

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A new type of plasma chemical reactor [1] based on reconstruction the standard vacuum chamber of the serial installation VU-1B was developed to carry out the deposition process of TiN-Cu nanocrystalline composite coatings. The structural scheme of the vacuum installation VU-1B is shown in figure 1 [2]. This plasma chemical reactor is based on the principle of Cu vapors metered injection into the region of chemical reaction Ti and N through a diaphragm's metering orifice. This diaphragm shield the penetration of titanium vapors to the cathode of the magnetron discharge (Fig. 1). Synthesis of composite TiN-Cu coatings on a substrate takes place with their concomitant modification by bombardment with low-energy ions of the plasma-forming gas (nitrogen) and titanium.

A comprehensive study of gas plasma generated by vacuum-arc and magnetron low-pressure discharges was a purpose of this paper. A single cylindrical Langmuir probe was used to research the plasma [3]. The probe had located directly on the axes of the planar magnetron, as well as the electric arc evaporator and at a different distance (from 45mm to 300mm) from the sources output apertures. In nitrogen atmosphere the measurements of plasma parameters were carried out. The probe characteristic was taken for each selected mode by which the floating potential, potential of plasma and electron's temperature were determined graphically. Further some results of measurements are given, in particular, it is given the magnetron's discharge current-voltage diagram at different values of the magnetron discharge current and constant pressure [Fig. 2].

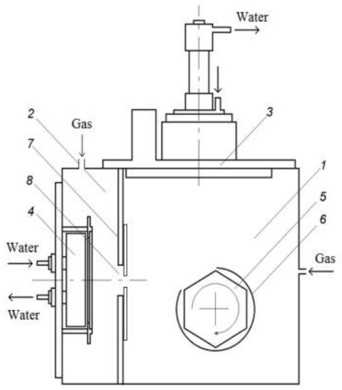

Fig. 1. The schematic diagram of the plasma-chemical reactor: 1-compartment of chemical reaction between Ti and N, 2-compartment of Cu vaporization, 3-arc evaporator of Ti, 4-planar magnetron with the copper cathode, 5-substrate holder, 6-shield, 7-diaphragm, and 8-metering orifice

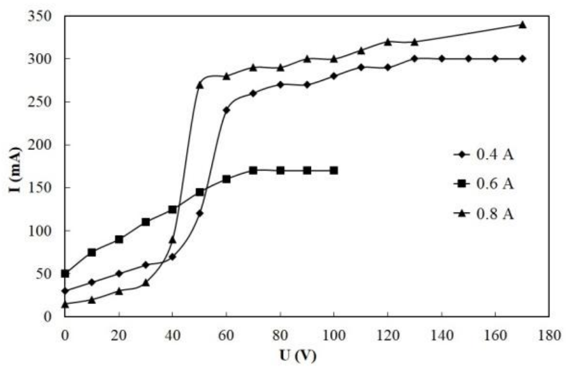

Fig. 2. The current-voltage diagram of magnetron discharge (P=8x10^{-3} Torr)

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GAS-DISCHARGE HIGH-FREQUENCY GENERATORS FOR MATERIAL PROCESSING

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The progress of acousto-and opto-electronics imposes heavy demands on the process of ionic etching of multicomponent materials, particularly, on piezoelectric crystals, that can not be etched using traditional gas and liquid etching methods [1]. The methods of the problem solution can be based on isolation of a high-frequency component of an electric field out of plasma for removal of displacement currents and recharging,. The investigated model (Fig 1) contains a plasma generator, formed by a ring cathode 1 and a housing 2, placed in a magnetic field. The housing is closed by a multicellular expander 3.

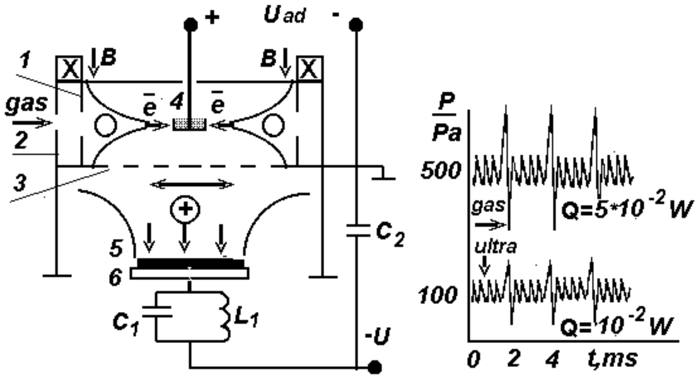

Fig. 1. Gas-discharge high-frequency generators

The operating chamber is evacuated down to pressure 0.1 Pa. Application of 600-800 V voltage to the plasma generator induces an auxiliary discharge in it (U_{ad}) with the current up to 1 A. The anode (crucible 4 with lithium niobate) is heated by intensive electron bombardment. The vaporous plasma of evaporated material enters the operating chamber through the expander cells. An extracting voltage (-U) of the order 3 KV with current up to 70 mA is applied to the electrode 6. A sample 5 is heated during 15 minutes to the temperature 600 K. The discharge voltage is increased up to 10-14 KV, and discharge current is decreased to 30 mA. Plasmoid rotation under the influence of an magnetic field and its interaction with an expander create conditions for periodic plasma penetration through the expander cells and generation of local inhomogeneities of the plasma density. This leads to stationary spatial instability of a high-voltage beam discharge. The inductive - capacitate circuit (C_1L_1) isolates a high- frequency component of an electric field with the frequency 5 MHz. This helps to remove a space charge from a lithium niobate sample surface at the expense of displacement current and recharging.

Simulation of etching on lithium niobate provides the etching speed of 5 mcm/h with the ion current density 0,5 mA/cm^2.

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FORMATION OF POWERFUL PLASMA FLOW FROM SUBSTANCE OF LIQUID ELECTROLYTE CATHODE*

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Plasma is formed predominantly from a liquid phase substance when using a liquid electrolyte as a cathode. Such a plasma is promising for creating a high-temperature vapor-gas medium in plasma-chemical reactors designed for energy-intensive plasma technologies, in particular, for the conversion of hydrocarbons into synthesis gas [1, 2]. To solve the problems of practical application requires research in the power range of tens of kilowatts. The aim of this work was to obtain a plasma flow of such capacities.

To create a plasma flow, plasma generator with a liquid electrolyte cathode and metal anode was developed. The walls of the generator discharge chamber were made of refractory material. As a liquid electrolyte cathode, aqueous solutions of sodium chloride with concentrations of 0.1-0.2 mol/l were used.

The distance between the liquid cathode and the metal anode was 20 cm. The power source was a three-phase, full-wave rectifier connected to the secondary windings of the step-up transformer. The voltage ripples was smoothed with a C-L-C filter. To study the energy characteristics, the technique described in paper [3] was used. The current was changed by the stepwise variation of the ballast resistor. It should be noted that the ballast resistor is not a required element in the electrical supply circuit. The plasma generator has an increasing current-voltage characteristic (fig. 1) and, therefore, its operating modes were stable at zero electrical resistance of the ballast resistor.

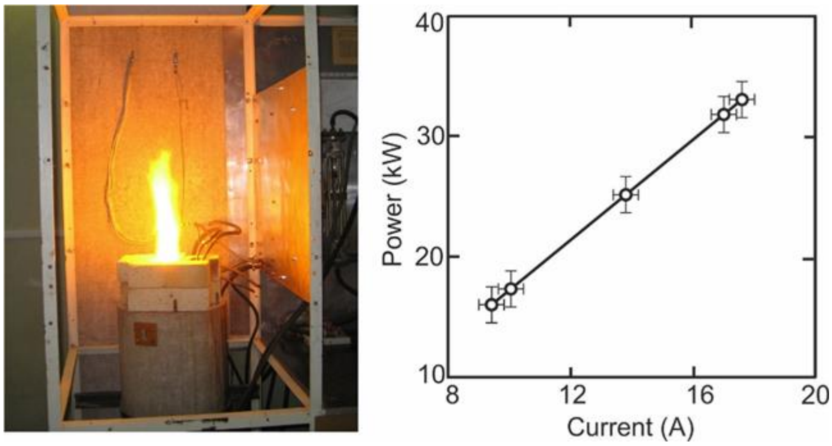

Fig. 1. Photo of the plasma flow at the exit of the plasma generator (energy consumption 30 kW) and graph of dependence of power from discharge current

During the operation of plasma generator, part of electrolyte was spent on the formation of plasma flow. The electrolyte loss was compensated by the addition of distilled water. In this case, the energy characteristics of plasma generator remained almost unchanged.

The paper studies the influence of electrolyte flow regimes through the cathode assembly on plasma flow formation.

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GENERATION OF TWO-COMPONENT BEAMS OF METAL IONS BASED ON VACUUM ARC WITH COPPER-CHROME CATHODE*

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The beams of metal ions generated in vacuum arc sources are widely used to improve the properties of the surface by the method of ion modification [1, 2]. The use of cathodes of complex composition in the sources allows one to obtain beams containing several types of ions. This expands the technological capabilities of vacuum arc ion sources and allows simultaneous processing of ions of various types to create complex alloys in the modified surface. The generation of two-component beams of metal ions in a vacuum arc source was investigated on a copper-chromium cathode model material available and widely used in industry. Composite cathodes with different contents of these metals were used. It is shown that a change in the proportion of metal ions in the cathode can be used to regulate the fraction of ions of these materials in the ion beam. The presented results may be useful in practice, for example, to modify the electrodes surface of dischargers and to create copper-chrome alloys in their surface with different proportions.

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GENERATION OF BEAM MULTICHARGED IONS OF BISMUTH*

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Beams of multicharged ions can be widely used both for physical research problems and for practice. Vacuum arc ion sources are currently considered promising for the generation of pulsed wide-aperture beams of multiply charged metal ions. At the moment, several methods have been developed and implemented to increase the charge states of ion beams in sources: by imposing a strong magnetic field on the cathode region of the vacuum arc [1]; with modulation of the discharge current [2]; when a dense electron beam is injected into a plasma [3]; with additional heating of the plasma in an open magnetic trap using microwave radiation from a powerful gyrotron [4]; as well as the implementation of a high-current arc with a short pulse duration [5]. This paper presents new results in the implementation of the last method.

At optimal discharge parameters (arc current levels of 3.5 kA and pulse duration of 400 ns), beams of bismuth ions with record charge states were obtained. The maximum charge of bismuth ions reached 19+. The results of the parameters optimization of the high-energy beams of -multicharged bismuth ions with ion energy in a beam reaching 1 MeV with an accelerating voltage of 60 kV are presented. The possibility of using such beams for surface modification of materials is discussed.

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COMPUTER SIMULATION OF ION BEAM-PLASMA INTERACTION*

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In the paper a two-dimensional axisymmetric hybrid numerical model of the interaction of an ion beam with a plasma is presented. The model is based on the kinetic approximation for the ions whereas the electrons are assumed to be a fluid [1]. To solve the Vlasov kinetic equation, the author's modification of the particle in cells method (PIC) is used [2]. The issues of accuracy and convergence of the created algorithms and the possibility of their implementation on the computing systems of modern architecture are discussed. It was shown that the magnetic flux can be expelled from the volume filled by the plasma due to the plasma-beam interaction. The dynamics of the magnetic field cavity formation depending on the characteristics of the ion beam and the background plasma is investigated. The comparison of the computer simulation results and the analytical assessments [3] has been done.

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A NEW TYPE OF NON-THERMAL ATMOSPHERIC PRESSURE PLASMAS SOURCE.

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The unique applications of Non-Thermal Atmospheric pressure Plasmas (NTAP) are associated with its enormous potential for providing technological capabilities for new products and technologies. In such plasmas, most of the electrical energy is deposited in the electron component of the plasma, while plasma ions and neutral components remain at or near room temperature, this allows the use of such a “cold” plasma for low-temperature plasma chemistry and for treating heat-sensitive materials, including polymers and biological tissues [1, 2]. Typical examples of NTAP sources are: corona discharge, glow discharge, dielectric barrier discharge (DBD) and non-thermal plasma jet (NTPJ).

DBD is a sequence of fast-flowing micro-discharges in a gas with a duration of several to tens of nanoseconds, when at least one of the electrodes is separated from the gas by a dielectric barrier made of glass, quartz, ceramic or polymeric materials. A distinctive feature of NTPJ sources is their ability to launch a thin jet of non-thermal plasma (based on discharge in argon or in helium) up to several centimeters in the external environment, where the electric field can be very low.

Figure 1 on the left shows the NTAP source, which combines the attributes of DBD (by discharge configuration) and NTPJ (by plasma jet formation).

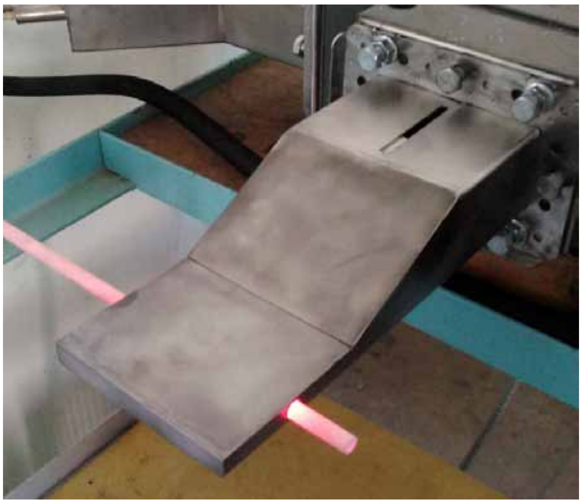

Fig. 1. Waveguide source NTAP with a ceramic discharge tube (left).
The moment of testing the non-temperature properties of an Argon plasma jet formed in a glass tube (right).

This device is a segment of a rectangular waveguide, short-circuited at the end and diaphragmed at the beginning, operating on the basic type of oscillations H_{01} [3]. The length of the segment is chosen close to the resonance. In the nearest to the short-range maximum field across the waveguide is placed discharge tube so that its axis is perpendicular to the electric field vector (DBD configuration). In this zone, the height of the waveguide is reduced to increase the E-field strength. Quartz, ceramics and glass were tested as the material of the discharge tube.

The advantage of the proposed device in comparison with DBD is the possibility of forming a stable long and thin plasma jet (Fig. 1 right). And unlike NTPJ, where the power consumed by the discharge is only a few tens of watts, in our device the microwave power supplied to the discharge can reach several kW.

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IMPROVING THE PERFORMANCE OF N_2 LASER WITH LONGITUDINAL DISCHARGE[*]

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The results of a study of an electric-discharge N2 laser pumped by a longitudinal discharge are presented. The discharge tube consisted of two sections 200 mm long and had a diameter of 18 mm into which nitrogen was blown at a pressure of 6-18 Torr. As a pump generator, an LC - inverter with a shock capacity of 4 nF was used, which was connected to a discharge tube through a coaxial cable, in parallel to which a peaking capacitance of 3.8 nF was placed. As a high-voltage switch, a TPI 10k / 20 brand tiratron was used. The charging voltage was 22-24 kV.

The main problems that arise in such lasers are to collapse the diffuse discharge with increasing discharge current density, which limits the amount of specific pump power and, accordingly, the output radiation energy. The use of various types of current interrupters providing an increase in the charging voltage to ~70 kV on the electrodes [1] or the installation of additional spark gaps for UV-preionisation of the discharge region [2] did not significantly increase the generation energy of the nitrogen laser, which was within 0.1-0.3 mJ, at a pulse duration of ~ 5 ns.

In our experiments to improve the stability of the diffuse discharge at higher values of the specific pumping power, a beam of runaway electrons was used both for preionizing the discharge volume and for the formation of the diffuse discharge. The generation of runaway electrons in the gas gap occurred when a high voltage (~ 25 kV) was applied to electrodes in the form of rings that had a sharply inhomogeneous electric field near their surface. The forming electron beam in the near-cathode region provided a good degree and homogeneity of pre-ionization, which allowed at the initial field strength on the gas tube E = 1.25 kV/cm, to realize in the diffuse discharge the maximum current density of 2-3 kA/cm^2, with a maximum specific pumping power of ~ 3 MW/cm^3.

The laser generation duration was equal to the pump pulse duration. At a wavelength of ~ 337.1 nm, radiation pulses with an energy of up to 3 mJ and a duration of up to 20 ns (FWHM) were obtained. Stability of discharge characteristics and generated radiation was maintained during laser operation at a frequency of up to 30 Hz [3].

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SPECTRAL CHARACTERISTICS OF ATMOSPHERIC PLASMA RF DISCHARGE AND LASER RADIATION PHILAMENT*

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Experimental studies of the spectral characteristics of plasma in the air of an RF discharge and in a filament of femtosecond laser radiation are presented. The ignition voltage of the high-frequency discharge had a sinusoidal shape with an amplitude of 10 kV, a discharge current amplitude of 2 mA, an oscillation frequency of 30 kHz. A filament in air arose during self-focusing of a 50-fs laser pulse with an intensity maximum at a wavelength of 950 nm.

In the emission spectrum of a plasma ignited by an RF discharge, emission bands of excited molecular nitrogen I, II of the positive system and N_2^+ I ions of the negative system are recorded. In the spectral range 200–280 nm, the fluorescence of $NO(A^2\Sigma^+–X^2\Pi, \nu_A=0)$ molecules is observed. In this type of discharge, the presence of excited neutral molecules $N_2(C^3\Pi_u, B^3\Pi_g)$ and ions of molecules $N_2^+(B^2\Sigma^+)$ is due to associative reactions of molecules $N_2(A^3\Sigma^+_u)$. Metastable states of $N_2(A^3\Sigma^+_u)$ molecules are formed in the afterglow in reactions between vibrationally excited ground state molecules $N_2(X^1\Sigma^+_g, \nu>39)$ and $N(^4S)$ atoms [1].

$N_2(X^1\Sigma^+_g, \nu>38) + N(^4S) \rightarrow N_2(A^3\Sigma^+_u, a'^1\Sigma^-_u) + N(^2D)$ $\quad k=10^{-11}\ cm^3s^{-1}$

$N_2(A^3\Sigma^+_u) + N_2(A^3\Sigma^+_u) \rightarrow N_2(C^3\Pi_u, B^3\Pi_g) + N_2(X^1\Sigma^+_g)$ $\quad k=1.5x10^{-10}\ cm^3s^{-1}$

$N_2(A^3\Sigma^+_u) + N_2(a'^1\Sigma^-_u) \rightarrow N_2^+(X^2\Sigma^+) + N_2(X^1\Sigma^+_g) + e$ $\quad k=0.1x10^{-11}\ cm^3s^{-1}$

The formation of nitric oxide $NO(X^2\Pi)$ in the atmospheric plasma of a high-frequency discharge is due to the presence of a high gas temperature, according to the Zeldovich mechanism. Due to the intermolecular interaction of the ground state molecules $NO(X^2\Pi)$ with molecules $N_2(A^3\Sigma^+_u)$, the formation of $NO(A^2\Sigma^+)$ molecules occurs.

$N_2(A^3\Sigma^+_u) + NO(X^2\Pi) \rightarrow NO(A^2\Sigma^+) + N_2(X^1\Sigma^+_g)$ $\quad k=7.0x10^{-11}\ cm^3s^{-1}$

On the plasma emission spectrum of fs laser radiation arising in the filament, neutral excited molecules $N_2(C^3\Pi_u, B^3\Pi_g)$ and ions of the molecules $N_2^+(B^2\Sigma^+)$ are recorded. The presence of excited molecules and ions of molecular nitrogen is due to the processes of multiphoton absorption and recombination with electrons. $NO(X^2\Pi)$ molecules are formed in the reactions of interaction between excited $N(^4S)$ atoms and O_2 molecules. The formation of $NO(A^2\Sigma^+)$ molecules occurs during the lifetime of the filament plasma due to inelastic collisions of $NO(X^2\Pi)$ molecules with electrons having an energy of ~ 5.5 eV [2].

$N_2(X^1\Sigma^+_g) + n\times hv \rightarrow N_2^+(B^2\Sigma^+); N_2^+(B^2\Sigma^+) + N_2(X^1\Sigma^+_g) \rightarrow N_4^+;$

$N_4^+ + e \rightarrow N_2(A^3\Sigma^+_u, C^3\Pi_u, B^3\Pi_g) + N_2(X^1\Sigma^+_g)$

$N_2(A^3\Sigma^+_u) + O(^3P) \rightarrow NO(X^2\Pi) + N(^2D)$ $\quad k=7.0x10^{-12}\ cm^3s^{-1}$

$N(^2D) + O_2 \rightarrow NO(X^2\Pi) + O(^1D)$ $\quad k=6.0x10^{-12}\ cm^3s^{-1}$

$NO(X^2\Pi) + e \rightarrow NO(A^2\Sigma^+)$ $\quad \Delta E=5,5$ эВ

Consequently, the existing mechanisms for the formation of $NO(A^2\Sigma^+)$ molecules in the filament plasma are less efficient than in the RF discharge plasma, which is also confirmed by a significantly lower luminescence intensity of the molecule NO $(A^2\Sigma^+–X^2\Pi, \nu_A=0)$ in the filament.

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PLASMA SOURCES AND EQUIPMENT

LAUNCH OF LOWER HYBRID WAVES TO A DENSE PLASMA COLUMN IN A STRONG MAGNETIC FIELD

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Modern open magnetic facilities for fusion research confine hydrogen plasma with densities form 10^{19} to 10^{21} m^{-3} in magnetic fields from 0.1 to 10 Tesla. Usually start-up plasmas in these facilities are created using plasma guns. Alternative sources of plasma are electron guns and several types of in-chamber discharges [1]. A DC discharge with plasma contacted with walls has some disadvantages for fusion experiments. Indeed, plasma temperature is decreasing and wall material contaminate discharge by heavy elements when the plasma touching chamber. Electrodeless plasma sources does not have such weakness.

In other hand, helicon sources based on magnetized discharge are widely used as low temperature plasma sources in plasma technologies [2]. They produce highly ionized, pure plasmas in magnetic fields 10-100 Gauss, using 10-100 MHz electromagnetic waves. Densities of this plasmas can reach 10^{19} m^{-3} but usually lower densities are used for plasma deposition or etching.

Application of helicon sources for producing start-up plasma in modern open facilities is good way to improve quality of the plasma. Increasing magnetic field strength lead to increasing lower hybrid resonance frequency Ω_{LHR} (1), which is equal to 1.4 GHz for target plasma parameters – plasma density is 10^{20} m^{-3} and magnetic field 3 Tesla. If one construct plasma source based on low hybrid waves frequency of the source should be lifted from MHz to GHz band.

$$\Omega_{LHR} = \sqrt{{\Omega_i}^2 + \frac{(\omega_{\mathrm{pi}} * \Omega_e)^2}{{\omega_{\mathrm{pe}}}^2 + {\Omega_e}^2}} \quad (1)$$

Effective and respectively cheap industrial sources – magnetrons working on 2.45 GHz and 915 MHz are suitable for use in this band. Wavelengths of these waves make waveguides more suitable for power transportation.

New open facility GOL-NB is under construction in Budker Institute of Nuclear Physics. Main goal of the GOL-NB facility [3] is study of plasma confinement in axially-symmetric linear trap with multiple-mirror sections. The facility consist of central trap with 0.3 T magnetic field strength, two multiple-mirror sections with corrugated or uniform field with maximal strength 4.5 T and mirror ratio 1.5. Arc discharge plasma gun was chosen as start-up source for this machine. Alternative way for creating plasma is helicon discharge in multiple-mirror section.

Experimental study of coupling of low-frequency electromagnetic waves with plasma in strong magnetic field was done on GOL-3 facility in 2015-2017 [4]. RF source based on industrial 2,45 GHz magnetron and simple ring capacitor antenna were chosen for first stage. Plasma was created by external source – plasma gun. Different types of antennae with enveloping conductors were measured and it was found that efficiency of power coupling about 50%.

New system for launch electromagnetic waves in low hybrid range is based on simple waveguide design with slot antenna placed on front side of the waveguide. In the work we will present results of simulation of whole RF system and first experimental results of launching of microwave power to GOL-NB facility.

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STUDY OF IGNITION AND BURNING OF PARTIAL DISCHARGE AT LOW VOLTAGE IN THE PRESENCE OF ELECTROLYTES

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Fig. 1 shows an experimental setup, which is a spark plug which has been filled with electrolyte (1.5% NaCl in water solution) to a level of 4.

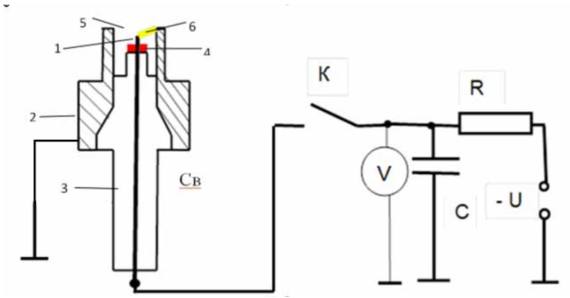

Figure 1. Scheme for generation of a partial discharge spark automotive: -U - constant voltage source 0 - 1000 V, R - resistance in the charging circuit, V - digital voltmeter, K – switch, Cв - automotive spark 1 - electrode 2 - electrode grounded, 3 - dielectric 4- place ignition incomplete PD, 5 - discharge gap, 6 - place ignition completed partial discharge.

The first stage PD - uncomplete discharge, shown in Fig. 2. It represents the current through the electrolyte surface, which heats and vaporizes a portion thereof, thereby initiating the formation of arcs which are further extended, covering the entire face. In fact, the incomplete discharge lasts about 10^{-1}s - capacitor discharge time constant. The discharge has a reddish color. Voltage of incomplete discharge ignition is about 600 V

Figure 2. The uncomplete partial discharge

Figure 3 Complete partial discharge

When the voltage reaches 730V, completed partial discharge occurs (Fig. 3), followed by bright white flash and a loud sound. Discharge time - less than 10^{-2} s. It seems that there has been a breakdown between the electrodes through the air. But 730V potential difference is insufficient to breakdown the interelectrode gap of 3 mm. In our opinion this is an incomplete discharge of its ultraviolet radiation initiates the breakdown in the air. Complete discharge current regulated ballast resistance Rb in the circuit automotive spark power.

Experiments with power rectified voltage from the voltage doubler circuit were also held. Figures 4 and 5 show the development of processes of incomplete and complete discharges, powered by the rectification circuit voltage doubler

Figure 4 (left). Incomplete partial discharge when supplied with rectified current. U = 600V, Rb >>100 ohm

Figure 5 (right). Complete partial discharge when supplied with rectified current. U = 600V, Rb <100 Ohm

MICROWAVE COMPLEX FOR OBTAINING LOW-TEMPERATURE PLASMA AT ATMOSPHERIC PRESSURE

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Over the past two decades, the scientific and technical community has made significant efforts to develop, maintain and use atmospheric non-thermal plasma (ANTP) in which ions and neutral components remain at or near room temperature [1,2]. The purpose of this work is to present a universal hardware complex, designed to generate both traditional low-temperature plasma and two types of ANTP in the R&D works on new materials and technologies, and also to intensify existing technological processes.

A hardware complex was designed and manufactured to produce low-temperature and/or non-thermal microwave plasma at atmospheric pressure. Non-thermal plasmas are generated by a diversity of microwave discharges such as dielectric barrier discharges (DBD), atmospheric pressure plasma jet (APPJ) and atmospheric pressure Argon streamer plasma. The equipment includes three types of applicators, waveguide/coax splitter, cable assembly and water load.

The hardware complex in the basic configuration consists of a microwave generator with HV power supply, a set of replaceable elements of the waveguide system, a water load, a 50 Ω cable assembly with N-connectors and one or several ANTP applicators (Fig. 1 left).

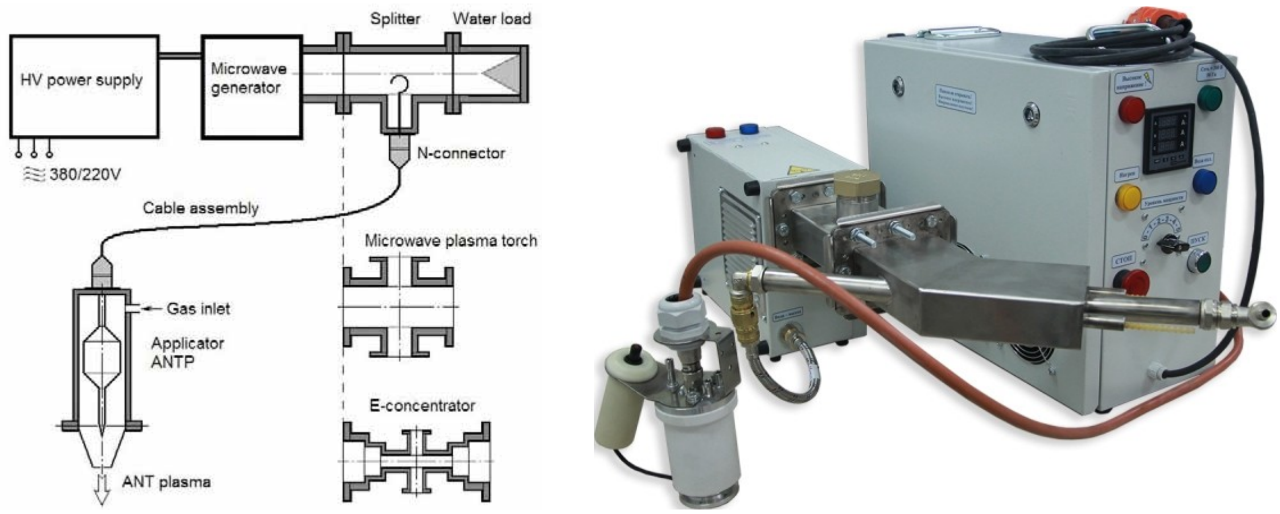

Fig. 1. Schematic diagram of components and blocks of the hardware complex (left).
The general view of universal hardware complex for obtaining of low-temperature and ANT plasma (right).

The basis of the presented hardware complex is a low-budget the 2.45 GHz magnetron microwave oscillator with a high-voltage power unit built on the magnetrons, transformers and capacitors used in microwave ovens for domestic and industrial use [3]. Between the output of the microwave generator and the load, the waveguide path elements from the next set can be placed. The microwave plasma torch on the main type H01 oscillations [4], E-field concentrator and an inductive-type splitter. ANTP applicator is connected to the splitter using a cable assembly.

The general view of the universal hardware complex of variable configuration for generation low-temperature microwave plasma at atmospheric pressure is shown in Fig. 1 (right). It is designed for both laboratory and industrial applications.

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SPECTRAL MEASUREMENTS IN THE PLASMA OF MICROWAVE AND MAGNETRON DISCHARGES

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1. The characteristics of Ar plasma emission of a low-pressure discharge (6-40 Pa) based on a household microwave (radiation frequency is 2.45 GHz, power is 800 W) oven are investigated. Spectrum measurements were performed using an AvaSpec 2048 fiber spectrometer in different sections of the working volume. It is shown that the intensity distribution of the Ar I and ArII lines is very non-uniform, namely, the maximum intensity is recorded near the chamber wall closest to the microwave emitter (position X_1 in Figure 1), the minimum is recorded in the middle section (position X_2) and the non-significant rise is recorded nearby the far wall (position X_3). Measurements of the degree of radiation coloration of LiF crystal samples placed in the plasma of this discharge at different distances from the microwave emitter showed that the staining profile correlates with spectral measurements. Consequently, the mechanism of coloration is due precisely to the bombardment of the crystal surface with plasma electron.

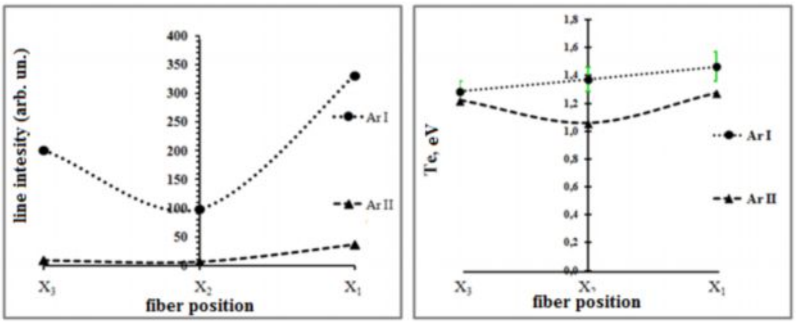

Figure 1. Distribution over the cross section of the working volume of intensity of the brightest spectral lines of argon (a) and the electron temperature determined from them (b). The coordinates xi correspond to the positions of the fiber shown in Fig. 3. P = 0.13 Torr

2. Similar spectral measurements were performed in a magnetron discharge plasma (current 250 mA, power 100 W). The dependence of the line intensity of the cathode materials (copper) and the buffer gas (argon) on the distance to the cathode-target is measured. It is shown that the intensity of the latter one drops significantly faster. This suggests that with a distance from the target, the concentration of atoms and argon ions also rapidly decreases, and their effect on the deposited film decreases, in particular, heating and defect formation. From the relative intensity of the lines, the excitation temperature of the plasma components was calculated in the framework of the model of local thermodynamic equilibrium (LTE) and the coronal model. It is shown that the temperature of all components () in the first case lies in the range of 0.6–1.2 eV; in the second case, it lies in the range of 0.7–1.4 eV and does not depend on the distance from the cathode. Thus, the LTE model can be used to estimate the plasma temperature in a given parameter range despite the violation of its applicability conditions for this case.

PLASMA EMISSION DURING COMBUSTION OF NI-AL POWDER MIXTURE

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The ionization ability of combustion reactions is well known and currently applied for magnetodynamic conversion of the energy of natural fuels. The formation of gas plasma in high-temperature combustion waves is caused by the volume thermo-and chemo-ionization of gaseous reaction products, as well as by the thermo-and chemo-stimulated emission of ions and electrons from the free surface of reacting condensed phases. The latter processes are the main source of gas ionization during the combustion of a number of heterogeneous systems (metal-metal powder mixtures, carbon, etc.) forming condensed products (intermetallic compounds, carbides, etc.).

In this case, substantially nonequilibrium states of the gas flowing from the reacting sample are observed: the excitation of the electron temperature up to 80000 K (Ti-Si system [1]) and energy spectrum of free electrons up to 60 eV (Ni-Al system [2]); second multiplicity ionization of metals (Ti-B, Zr-B systems [3]). Such systems are interesting as an autonomous chemical source of a concentrated stream of charged particles, for example, as a plasma cathode for gas discharge, however, their emission properties have not been fully studied.

In this work, plasma emission was studied during the combustion of a Ni + 31.5wt.% Al powder mixture. Reaction was conducted according to the scheme Ni + Al → NiAl + 117.7 kJ/mol under an argon atmosphere at a pressure of 10÷ 100 kPa. Nickel (PNC-UH1, with a purity of 99.85wt.% and a particle size not more than 20 μm) and aluminum (ASD-4, with a purity of 99.7wt.% and a particle size not more than 10 μm) were used as components of the mixture. The shape of the samples was as follows: cylinders 20 mm in height and 20 mm in diameter, with a porosity of 40%. An electric probe in the form of a tungsten wire with a diameter of 0.2 mm was placed at a distance of 1.5÷2.0 mm from the sample surface inside a special cavity. An alternating voltage with an amplitude of 1.5÷400 V and a frequency of 50÷1000 Hz was supplied through an electrical circuit with a reference 200 Ω and ballast 2 ÷ 74 kΩ resistances.

Combustion was initiated by the heated electrospiral and monitored by video recording. Electric current proportional to the degree of gas ionization appeared between the sample and the probe during the propagation of combustion in the circuit. The current signals in the circuit (i) and the probe voltage (V) were transmitted through a high-speed analog-to-digital converter (data acquisition frequency is 10 MHz) to the computer and processed as a set of current-voltage characteristics (CVC) of the probe for different times relative at the moment when the current appeared. The electron temperature of emission plasma (T_e) was determined by the Langmuir method [4]. For the positive steep part of the CVC with a voltage amplitude of 15V, the experimental data were interpolated by a linear function $\ln i = a + bV$. The electron temperature was calculated by the formula: $T_e = e(kb)^{-1}$, where e - electron charge, k - Boltzmann constant.

The experiments have shown that combustion propagates with a linear velocity of 4.6 cm/s. When the reaction wave passes by the probe for the time t <50 ms, the electron temperature of emission plasma increases to the level T_e = 14000 K. It is significantly higher than the equilibrium adiabatic combustion temperature of the mixture Ni + 31.5wt.% Al (T_c= 1911 K [5]). In the interval $t = t^* \approx 50 \div 500$ ms, the T_e value decreases and approaches T_c in the interval $t = t^*$> 500 ms. It can be concluded that the intervals t^*, t^{**} correspond to the modes of chemo-stimulated and thermal emission of charged particles. Analysis of the CVC shows that with increasing the voltage up to 400 V, the current reaches 0.2 A, while the gas discharge between the sample and the probe changes from non-self-sustaining to different forms of self-sustaining discharge: Townsend, abnormal glow, and spark. The first form takes place only with the support of chemo-stimulated emission of charged particles from the reacting sample (interval t^*).

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CALCULATION MODEL OF THE PLASMA LOAD MATCHING WITH THE CURRENT SOURCES BASED ON EXPLOSIVE MAGNETIC GENERATOR *

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The need for efficient energy supply of pulsed plasma loads imposes strict requirements on the front and amplitude of the current generated in the load [1]. Investigations of a pulsed current source based on an explosive generator (EMG) show its advantages over a capacitive storage device primarily due to the growing character of the power of this type of current source. The experiments presented in [2] confirm this fact. However, it should be noted that a correct engineering calculation of the parameters of the EMG and matching of its work with a variable plasma load are required for the implementation of these advantages in practice at the design stage of the system. The need for such models is especially great for explosive experiments with EMG, which are relatively expensive.

The use of electrical models for the analysis of linear circuits is impossible in this case because of the pulsed character of the sources, and nonlinear dynamics of current – voltage characteristics of the plasma load. The main nonlinearity is related to the change in space and time of the current shell shape of the plasma in the load, which is mainly inductive. At the same time, magneto hydrodynamic calculation for spatial geometry is complicated and provides extra information for engineering and design engineering. In this paper, the problem is considered for the matching scheme of EMG and pulsed plasma accelerator at the amplitudes of discharge current up to 2.5 MA. Experiments have shown that the dynamics of the inductance of the load is a critical parameter in this problem. Due to the self-consistency of the parameters of the system, which includes an explosive generator, switching elements and plasma load, the calculation of the pulse current in engineering models requires reliable assumptions. The main assumption taken as a basis in this model is the use of a time-dependent shell model with a concentrated mass. The specified simplification allows us to reduce the model of the motion of the current sheath to a one-dimensional model of the motion of the concentrated mass used, which greatly simplifies performing a series of calculations and optimization design of EMG under a specific load. The dynamics of the shell mass change is consistent with the experimental data.

The obtained data are compared with experimental data obtained in real experiments with the pulsed plasma accelerator powered from EMG. It is shown that the built model has sufficient accuracy for preliminary calculations of matching the operation of the EMG with the dynamics of the plasma accelerator.

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PLASMA SOURCES AND EQUIPMENT

INFLUENCE OF THE HOLES DIAMETER IN THE PERFORATED ELECTRODE ON THE PARAMETERS OF ELECTRON BEAM GENERATED BY FOREVACUUM PLASMA ELECTRON SOURCE

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Plasma technologies and sources of electrons based on a plasma cathode that are actively developing in recent times require continuous improvement of existing equipment. Forevacuum plasma electron sources, able to function in a pressure range of a unit and tens of pascals, allow electron-beam processing of both conductive materials and dielectrics without the use of additional means of compensation for the surface charge [1]. To stabilize the plasma emission boundary, they traditionally use either a grid of refractory material or a perforated electrode with a thickness of not more than 1 mm. The use of the grid allows to increase the efficiency of emission from the hollow cathode plasma, but at the same time the probability of its burnout at the breakdown of the accelerating gap is quite high. The use of a perforated electrode significantly increases the operating time of the electron source, even during the breakdown of the accelerating gap. However, when the electron source operates at maximum parameters, i.e. upon receipt of electron beams with a capacity of more than 5-6 kW, the thermal load on the perforated electrode increases, which ultimately also leads to its destruction. This paper presents the results of experiments to optimize the emission electrode in a plasma cathode electron source. The optimal thickness of the perforated electrode and the diameter of the emission hole are found. With this thickness, the maximum efficiency of electron extraction from the plasma in the range of operating pressures of the source is 10-30 Pa.

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THE EFFECT OF COMPRESSION PLASMA FLOWS ON THE METAL FILM-SUBSTRATE SYSTEM

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Surface engineering is a well-developed field of materials science. One of the surface engineering directions is high-energy surface treatment in order to modify its properties. Among the methods most developed are high-current electron and power ion beams processing [1], pulsed plasma flows [2], broadband [3] and laser radiation [4].

The report presents investigation results of the effect of compression plasma flow [5,6] on a metal film-substrate system in a pulsed-periodic mode. Critical modes of compression plasma flow influence to the surface were defined. The changes in the microhardness of the film and its adhesion were recorded. Also the changes of coating porosity and its microrelief were studied. The results have been discussing.

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THE ION BEAM GENERATION IN THE SELF-MAGNETICALLY INSULATED ION DIODE

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The studies of the plasma formation on the anode surface of the self-magnetically insulated ion diode were performed. The plasma formation is carried out by the voltage prepulse of negative polarity. The electrodes have a focusing geometry to provide ballistic focusing of ion beam. The anode was a graphite focusing electrode of rectangular cross-section. The diode cathode was designed in form of a grid from stainless steel. During the studies the anode and cathode configuration which provides uniform plasma formation was obtained. The experimental data of the current density and energy distribution over the ion beam cross section depending on the plasma formation conditions at the anode surface were obtained.

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Partial Discharge Analysis Through Lissajous Figure at Low Air Pressures

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the condition of electrical insulation is significant to the safety of electric power systems, especially to the More Electric Aircraft(MEA) that carries hundreds of people. The property of insulation will be reduced by aging and degradation which caused by partial discharge (PD). This has become a topic of extensive research and investigation.

This paper represents the PD detection in terms of Lissajous figures which is a composite of two orthogonal oscillations with integral proportional frequencies. It can be used to calculate the total charge of PD transferred per cycle and the total energy of PD per cycle, thus the average charge and energy of a single PD activity can be recognized accompany with the current pulse PD detection method based on IEC 60270.

Fig. 1.Typical Lissajous Figure of PD

The accumulated voltage value between the bottom and the top of the side on the right hand side that across the X axis can be taken as *ΔU*. There is a capacitor *C* connected in series with the testing sample, thus the discharge amount in a half cycle can be calculated with the formula below:

$$\Delta Q = \Delta U \times C \qquad (1)$$

The total energy of a full cycle is the area of the parallelogram, which can be calculated trough the chequer grid circled by the parallelogram.

The calculated charge amount and energy reflect the condition of the insulation, which is helpful to the evaluation of the property of insulation.

DEVELOPMENT OF ELECTRON-BEAM EQUIPMENT AND TECHNOLOGY OF LAYER WELDING OF THE WIRE IN THE CONDITIONS OF ADDITIVE TECHNOLOGIES

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Currently, more and more often, a wide range of additive technologies (or 3D printing technologies) are used to solve problems of obtaining metal products of complex shape with anisotropic properties. If it is necessary to print thick-walled parts with less accuracy (a few millimeters) and greater productivity, the method of dimensional electron beam surfacing with wire is promising. In the period from 2015 to the present, the modular installation of electron beam fusion of powders and surfacing with wire was created and constantly modernized at NI TPU. At its core is a vacuum chamber with an electron-beam gun with a plasma emitter and modular manipulators, providing the possibility of layer-by-layer alloying of powders (EBM) or dimensional deposition with wire. The software provides the possibility of modular replacement and synchronized control of all installation organs, according to the task, using digital G - codes. Printing was carried out at an accelerating voltage of 30 kV and a beam current of 15 to 20 mA (depending on the distance from the substrate), thus, the input power varied from 450 to 600 watts. The focused beam (diameter 150 μm) moved in a circular scan 4 mm in diameter. The frequency of the beam on the scan of 1000 Hz. The wire was fed to the sweep area, and the sample geometry was achieved by moving the table along three axes. The distance between the tracks (hatching distance) was 4 mm, and the layer height was 0.8 mm, the movement in the horizontal plane was zigzag. The sample construction scheme is shown in Figure 1.

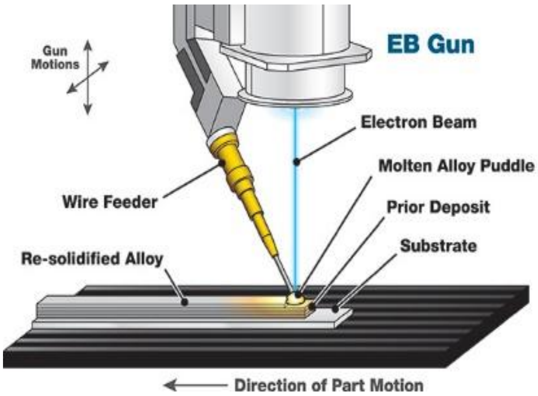

Fig.1.

Fig.2

During the work, samples from wires of titanium alloy Ti-6Al-4V and steel AISI 304 were printed on an electron-beam 3D-printer. To study porosity and mechanical properties, a continuous sample of titanium alloy in the form of a cube and from steel in the form of a rectangle was obtained, fig.2. The study of the quality of the formed samples on the subject of porosity and structural heterogeneity, and hence the mechanical properties was carried out in the work of non-destructive testing methods using computed tomography and methods of mechanical testing and metallography. It is shown that the regulation of the modes of radiation exposure and modes of wire feeding and beam scanning allows obtaining titanium and steel products with high microstructural uniformity and satisfactory mechanical properties, but the problem of reducing macro porosity requires new approaches to optimize microstructural uniformity and porosity.

DEPOSITION RATES OF CU, CR, AND SI IN AN IMPULSE MAGNETRON DISCHARGE WITH HOT TARGET*

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Magnetron sputtering devices ensure deposition of thin films with outstanding physical properties and high quality. The constant demand for even better performance of coatings and their production processes stimulates the development of novel approaches in deposition techniques. One of the promising concepts is an impulse magnetron with hot (or liquid) target (IMHT, or IMLT, correspondingly [1].

We studied the deposition rates of Cu, Cr, and Si obtained in a magnetron device with thermally insulated target [2]. In each case, at first, the direct current discharge was initiated, and after the stabilization of parameters at a power level specific for the target material, the series of high-current impulses were applied to the target. The deposition rates were measured by weighing method. The prepared coatings were analyzed with scanning electron microscope.

The results demonstrate that the deposition rates in IMHT (IMLT) regimes are nearly the same as in the corresponding DC discharge modes. However, the structure of coatings becomes substantially denser that indicates the elevation of ion fraction in the impulse regimes and thus reveals their benefit of tailoring the coating properties.

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PLASMA SOURCES AND EQUIPMENT

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STUDY OF CHARACTERISTICS OF THE LOW-TEMPERATURE PLASMA SOURCE BASED ON THE PIEZOTRANSFORMER*

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Nowadays, it is of current interest to create and use devices for generating low-temperature non-equilibrium plasma at atmospheric pressure for treating various surfaces, including thermally unstable, as well as creating plasma-activated media (including biomedical) [1]. The most common sources of "cold" plasma have the disadvantage that is the difficulty of selecting operating modes. In addition, most of these sources have relatively large overall dimensions and can work only with noble gas pumping.

The proposed design of the source (generator) of low-temperature plasma [2] (Fig. 1) is compact and allows to use three different operation modes. The plasma source is a dielectric tube 4 fixed in a rigid case 5, forming an ionization chamber 3, inside which a piezotransformer 1 is installed. Piezotransformer configured to convert a low-amplitude alternating voltage from generator 6 into a high voltage at a discharge electrode 2 at the output end of the piezotransformer 1. This design of a low-temperature plasma generator contains a dielectric cap 9, which fits piezotransformer output end 1 tight and allows changing the thickness of the dielectric layer 10. This fact permits the source to operate in a mode of dielectric barrier discharge at a short distance from the outer dielectric 10 (1-3 mm). It is possible to create a direct piezo-discharge without a dielectric cap 9. The pumping of a noble gas through a dielectric tube allows obtaining a plasma jet with adjustable parameters of low-temperature plasma.

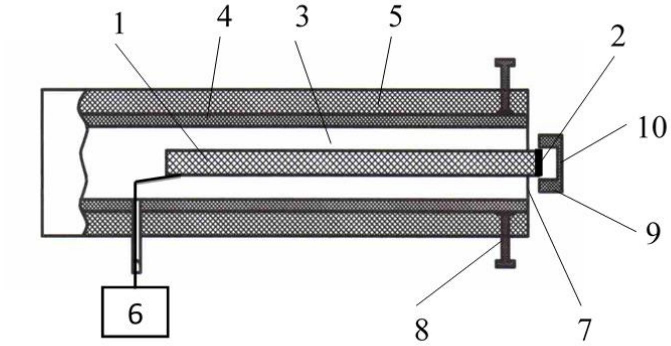

Рис. 1. The low-temperature plasma source based on the piezotransformer.

The rotational and oscillation temperatures of the electrons in the discharge were obtained from the emission spectra for all three operation modes of the low-temperature atmospheric pressure plasma source. The distribution of the electric field near the discharge gap was obtained using a probe operating on the Pockels effect. The possibility of treating biological objects by low-temperature plasma from this source was shown, as well as obtaining plasma-activated media used to study the mechanisms of multifactor effects on living tissue cells and to search for new possibilities of therapy of oncological formations with increasing efficiency of existing techniques.

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FEATURES OF LOW PRESSURE ARC DISCHARGE WITH THE COLD HOLLOW CATHODE IN A MAGNETIC FIELD[1]

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Low pressure arc discharge is widely used to solve scientific and applied problems [1]. In particular, on the basis of a low-pressure arc discharge, a plasma source with a cold hollow cathode is created, which allows generating plasma of inert and active gases [2]. Due to the low discharge voltage, this plasma source is advantageously used as a source of electrons for stable ignition and discharge of a high-current non-independent low-pressure glow discharge with a hollow cathode [3]. In [3], the operating pressure at which a non-independent glow discharge is stably functioning is limited to a minimum operating pressure of about 0.2 Pa, at which the arc discharge with a cold hollow cathode in crossed electric and magnetic fields is still stable. The purpose of the study was to identify the possibility of stable operation of the arc discharge with a cathode spot at lower operating pressure values. To this end, the maximum operating voltage applied to the discharge gap was increased from 55 V to 120 V at a fixed value of the axial magnetic field.

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PLASMA SOURCES AND EQUIPMENT

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PARAMETERS AFFECTING THE OPERATION OF ECR PLASMA SOURCE

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ECR (Electron Cyclotron Resonance) Plasma source was studied as apart of heating mechanism in the studies of beam plasma target interaction in plasma linear devices. Microwave of 2.45 GHz was launched radially with power ranging from 200 watts to 1400 watts. Plasma simulation was performed to study the effect of magnetic field intensity on the position of ECR layer. Hydrogen gas was fed to the chamber through flow meter with pressure ranging from 2×10^{-4} Torr to 8×10^{-3} Torr. Two identical magnetic coils were used with current ranging from 90 A to 160 A. Radial and axial Langmuir probes were installed for plasma profile measurements. Electron temperature was measured and ranging from 7 to 16 eV with electron plasma density range of 8×10^{15} m^{-3} to 6×10^{16} m^{-3}. Electron temperature groups were studied by means of EEDF. It was found that the shape of EEDF was affected by the applied magnetic field and gas pressure.

MODEL COMPOUND MIXTURES FOR STUDYING THE MAIN TRENDS OF VOLATILE ORGANIC COMPOUNDS CONVERSION IN PROCESSES OF AIR CLEANING BY PULSED DISCHARGES*

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Pulsed discharges of atmospheric pressure are widely used to clean the air from ecotoxic volatile organic compounds (VOC). These discharges are the source of a non-equilibrium low-temperature plasma. The use of such type of plasma allows to carry out processes without substantial heating of the air flows, that promises energy savings. However, due to the wide variety of chemical properties of VOCs, they are removed with different efficiencies and different mechanisms. In addition, a large variety of the discharges and experimental realizations under study does not allow to compare their energy efficiency correctly. It can be said that there is a need to develop a unified approach for the study of air purification processes from VOC vapors and their energy efficiency. Previously, a method of standard mixtures was proposed, which allows to estimate the qualitative parameters of the plasma (relative reactivity of the components) and the energy parameters of the processes [1,2]. The main idea of the method is to use specially selected mixtures of components and gas media to identify the main laws and processes taking place in the air stream processed by the plasma. There is a reason to believe that this approach can be recognized as universal.

This report provides an overview of the development of this method over the past 2 years. A base part of the experimental setup, a high-voltage generator was used, which formed a voltage pulse of negative polarity in air with a current amplitude of 200 - 400 A; voltage pulse amplitude of 100 - 120 kV; voltage pulse full width at half maximum of 15 - 30 ns; pulse energy of 0.4 - 0.6 J and pulse repetition frequency was 10 Hz. For an additional comparison, widely studied compounds were used. The following groups of model mixtures in various gaseous media based on N_2 and O_2 were selected:

1. **Model mixture (I)** of components: hexane (C_6H_{14}), toluene ($C_6H_5CH_3$), acetone (CH_3COCH_3), ethyl acetate ($CH_3COOC_2H_5$), butyl acetate ($CH_3COOC_4H_9$) allows to access the relative reactivity of components of well-known solvents and to identify the main channels for their removal, as well as to estimate the energy yield of the removal process.

2. **Model mixture (II)** of components: carbon tetrachloride (CCl_4), chloroform ($CHCl_3$), methylene chloride (CH_2Cl_2), dichloroethane ($ClCH_2CH_2Cl$) makes it possible to assess the relative reactivity of halogen-containing components and to identify the main channels for their removal.

3. **Model components (III):** styrene ($C_6H_5CHCH_2$), MMA ($CH_2CCH_3COOCH_3$), TCE (CCl_2CHCl) and PCE (CCl_2CCl_2) as unsaturated compounds both in the individual state and in combination with separate components of mixtures **I** and **II** (toluene and CCl_4) for comparison.

The use of mixtures **I** and **II** in gas media with different oxygen content showed a low contribution of processes involving oxygen and ozone into the removal process. Moreover, oxygen serves as a deactivator of active plasma particles. On the other hand, components from list **III**: styrene and MMA are efficiently removed by ozone, therefore O_2 increases efficiency. PCE and TCE are removed by mechanisms both with the participation of oxygen and ozone, and by mechanisms with the participation of active forms of nitrogen. Thus, it has been shown that reactive oxygen species, including ozone, are the main active reactants in the case of unsaturated compounds (styrene and MMA and partly for TCE and PCE), but ineffective at removing many other components.

Obviously, these model mixtures and conditions can be used to compare various types of discharges. The found regularities will be useful for the development of new air purification technologies.

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THE USE OF MAGNETRON SPUTTERING TO SYNTHESIS BORIDE NEUTRON-ABSORBING COATINGS*

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When storing spent nuclear fuel, the presence of α-radioactive nuclides can lead to the appearance of neutrons in the (α, n) – reaction. These neutrons can cause the regeneration of a part of the fuel. In this connection, it is necessary to take measures to reduce the risk of a radiation accident. For the manufacture of protective containers used neutron-absorbing constructional materials [1].

As the cost of bulk doping with absorbing elements and related technological difficulties grows, the use of neutron-absorbing coatings becomes most preferable. The most widespread coatings of amorphous boron carbide [2]. We have proposed the idea of using coatings with the B-Ti system for neutron absorption. In the previous work, the effectiveness of this approach was shown [3].

This paper presents the results of experiments on the magnetron sputtering of titanium boride coatings on the surface of structural stainless steel. Used magnetron sputtering system DC VUP-5M. For sputtering, a composite cathode target Ti + B_4C was used. As a plasma-forming gas was used Ar, the residual pressure of which was ~ 2×10^{-3} Pa. The voltage applied to the cathode target varied from 200 to 600 V, with a current of up to 70 A. The resulting coating was a two-phase titanium boride compound: the matrix is Ti_2B_5 (~ 70%), implantation phase - TiB_{12} (particles with a diameter of up to 0.5 μm). At the maximum applied voltage within 30 minutes, a coating ~ 370 nm thick was formed. The coating has a columnar structure characteristic of magnetron deposition (Figure 1).

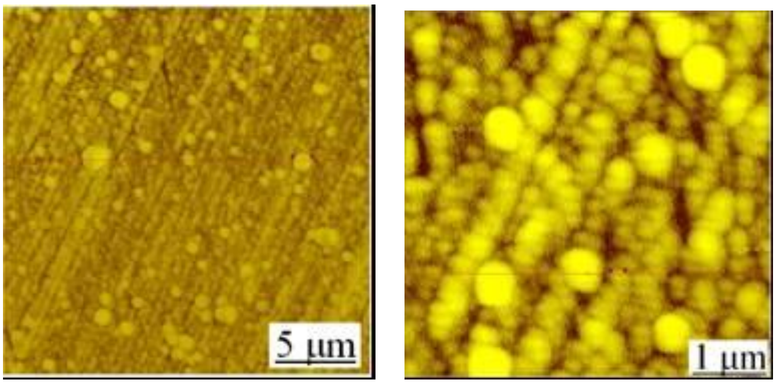

Fig. 1. Scanned (SPM) image of titanium boride coating surface

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STRUCTURE OF AN ELECTRO-EXPLOSIVE COATING OF THE ZNO-AG SYSTEM*

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The analysis of the results obtained shows that the formed coating is a homogeneous composite material. According to the structural morphology and the etching contrast, the forming coating consists of a light silver matrix and dark ZnO inclusions with dimensions varying from 0.3 to 0.5 μm. The elemental composition of the coating was analyzed by X-ray microanalysis methods. Analyzing the results presented it can be noted that the concentrations of copper, zinc and silver in the coating vary slightly in its thickness. This fact also indicates the structural homogeneity of the coating obtained.

Atomic force microscopy was performed in the coating layer located at a distance of 10 μm from the coating surface, as well as at the interface between the coating and the copper substrate. Since the electro-explosive coating is formed by a silver matrix and ZnO powder particles located in it, small particles of ZnO powder can be crumbled out of the matrix during the preparation of thin sections. In this case, pores, i.e. dark areas 30 to 100 nm deep and 2 to 5 nm wide are formed at the site of fallen particles. ZnO particles are dispersed to 2 ... 5 nm in the process of an electric explosion during the formation of a pulsed plasma jet of products of the electric explosion of conductors.

Separate large particles of various shapes with sizes ranging from 10 to 15 nm are also detected. These ZnO particles do not crumble out of the silver matrix during the preparation of the thin section; they are sharply highlighted in color, i.e. they are lighter than the matrix. They are randomly located in a silver matrix. Large particles have a complex structure. They are composed of spheres (globules) with a diameter of 2 to 5 nm (these are small spherical particles described above). The ratio of the silver matrix, large and small particles of ZnO powder is 0.6: 0.15: 0.25. Taking into consideration the fact that large ZnO particles consist of smaller globular ZnO particles then the ratio of the silver matrix and the inclusions of ZnO powder is 0.6: 0.4. This ratio is proportional to the content of ZnO powder and silver foil used for electro-explosive coating. The average roughness of the surface profile of the ZnO-Ag system coating is 100 nm.

Thus, it was possible to identify an important structural element - the ZnO globule, i.e. a spherical particle with a diameter of 2 to 5 nm. There is a multi-level hierarchical structure of the ZnO-Ag coating system, which is based on uniform spherical ZnO particles with a diameter of 2 to 5 nm. The fact that the ZnO inclusions, located in the silver matrix are made of a single structural unit is a very important argument in favor of the fractal mechanism for the formation of an electro-explosive coating. Such particles constitute the first hierarchical level of the structure of the electro-explosive coating of the ZnO-Ag system. The second hierarchical level consists of globules -large particles of various shapes with sizes ranging from 10 to 15 nm, which, in turn, form the sediment of micron-sized particles of irregular shape, detected by scanning electron microscopy.

At the boundary between the coating and the copper substrate there are visible dark depressions ranging in size from 10 to 15 nm. Aforementioned large ZnO particles crumbled out of them. In addition, surface periodic structures appear at the coating/substrate boundary in a silver matrix. The secant held perpendicular to these structural formations suggests that the wavelength in them is on average 3 nm. The structures are the residual nanorelief of the surface. After the end of the impact of a pulsed plasma jet of products of the electrical explosion of conductors on a substrate and cooling the surface, the induced relief is fixed in the form of surface periodic structures. They can be formed due to evaporation, melting of the surface and displacement of the melt by excess vapor pressure, thermocapillary phenomena and thermochemical reactions, thermal deformations, the emergence and development of various instabilities such as Rayleigh-Taylor, Kelvin-Helmholtz, Marangoni and others. In general, the phenomenon is universal and is an example of self-organization in a system with no initially selected directions and structures. The energy regimes for obtaining surface periodic structures correspond to heating the material to a temperature approximately equal to the melting point (lower limit), but not higher than the temperature of developed evaporation. This regime was used in electro-explosive coating in the present work. Surface profilometry showed that the roughness parameter of the electro-explosive coating of the ZnO-Ag system is 73 nm. In this case, the maximum profile protrusion reaches 536.85 nm, and the depth - 497.5 nm.

* The present work was performed within Russian Science Foundation project No. 18-79-00013.

TI-ZR COATINGS FORMED ON THE TITANIUM IMPLANT SURFACE BY THE ELECROEXPLOSIVE METHOD*

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According to the morphology and etching contrast, the formed coating can be divided into two sublayers. Near the interface, sublayer 1 has a columnar structure, and sublayer 2 has a dendritic structure. It can be assumed that sublayer 2 resulted from melting and subsequent high-rate crystallization of the surface layer of the substrate (titanium-based alloy) initiated by an incident plasma flow formed by an electric explosion of the titanium foil with the zirconium powder placed on it. Sublayer 1 is the actual coating of the Ti-Zr system.

The X-ray microanalysis of the elemental composition at points reveals atoms of other elements along with titanium and zirconium atoms. It is clearly seen that along with the elements characteristic of the titanium-based alloy, carbon and oxygen atoms are present in the coating. Carbon atoms are detected only in the surface layer, and oxygen atoms are present throughout the coating. Based on the results of the elemental analysis, it can be assumed that the formed coating is multiphase and should contain, along with the Ti-Zr alloy, carbide and oxide phases.

The performed investigation revealed the presence of three phases in the surface layer: the main is the α-modification of the TiZr alloy (81.3 % by volume), the fraction of zirconium oxide ZrO (9.5% by volume) and titanium carbide TiC are significantly smaller (9.2 % by volume). Thus, the X-ray diffraction analysis results are in good agreement with the X-ray microanalysis results. The presence of oxide and carbide phases in the surface layer of the coating is obviously due to technical vacuum of the working chamber of the electroexplosive alloying installation and the use of a graphite electrode.

The defect substructure of the coating was studied by transmission electron microscopy of thin foils. Foils were prepared by ion sputtering of plates cut from the specimen bulk in the cross section of the coating. It is clearly seen that the surface layer of the coating has a nanocrystalline structure whose crystallites vary in size from 20 to 100 nm. The underlying layer up to 30 μm in thickness has a submicrocrystalline structure. The size of the crystallites forming this sublayer varies from 200 to 450 nm. The layer located at a greater distance from the coating surface has a bimodal structure. Along with crystallites 200–300 nm in size, it has crystallites tens of nanometers in size. As the coating-substrate interface is approached, the relative content of nanosized crystallites increases. Based on the X-ray microanalysis results on the elemental composition of the coating, it can be assumed that nanoscale crystallites are oxide phases based on titanium and zirconium.

The microstructures show that the grains of one phase (appearing dark-grey) are surrounded by the continous or discontinous layers of another phase (appearing light -grey). This phenomenon is intimately connected with the so-called complete and incomplete wetting of grain boundaries by the second solid phase both in titanium as well as in the zirconium-based alloys.

The Ti-Zr coating formed by electric explosion had the following parameters (opposite to the wear resistance of the material): wear parameter $5.5 \cdot 10^{-4}$ $mm^3/N \cdot m$, friction coefficient 0.572, hardness 3730 ± 0.495 MPa, and Young's modulus 73.8 ± 6.19 GPa. The uncoated specimen had the wear parameter $6.5 \cdot 10^{-4}$ $mm^3/N \cdot m$, friction coefficient 0.376, hardness 3630 ± 260 MPa, and Young's modulus 84.3 ± 7.62 GPa. Formation of a Ti-Zr coating is accompanied by an insignificant (by 18%) decrease in the wear parameter (an increase in the wear resistance) of the surface layer, a 1.5-fold increase in the friction coefficient, a slight (by 3%) increase in hardness, and a decrease in Young's modulus by 14%.

The electroexplosive method is used to form a Ti-Zr coating with a thickness of at least 50 μm on the surface of the dental implant made of titanium-based alloy. The coating is found to be multielement and multiphase. It was shown that along with the Ti-Zr-based solid solution, carbide and oxide phases are present in the coating. It was found that the coating formed by the electroexplosive method has a submicro-nanocrystalline structure. It was revealed that the formation of a Ti-Zr coating is accompanied (relative to the uncoated substrate) by a slight (18%) decrease in the wear parameter (increase in the wear resistance) of the surface layer, a 1.5-fold increase in the friction coefficient, a slight (3%) increase in hardness, and a decrease in Young's modulus by 14%.

* The present work was performed within RFBR project No. 18-32-00075.

DEVELOPMENT OF ENVIRONMENT FRIENDLY TECHNOLOGY OF GENERATION OF ELECTROEROSION-RESISTANT COMPOSITE COATINGS FOR SWITCHES OF HIGH-POWER ELECTRIC LINES, WHICH COMBINES ELECTRO-EXPLOSIVE SPRAYING AND ELECTRON-ION-PLASMA MODIFICATION*

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One of the components of Russian national security until 2020 (approved by Presidential Decree No. 537 of 12.05.2009) is to ensure energy and environmental security. Enhancing fire safety, reliability and profitability of electrical installations and, in particular, their electrical contacts is one of the priority areas for ensuring energy security. Thus, development of new materials for electrical contacts is an important problem. Promising methods for formation of such coatings include electrospray deposition by pulsed multiphase plasma jets. In that respect, the problem seems to be relevant.

Promising direction of development of method of electrospray coating of composite materials is modification of coatings by high-intensity electron beams. Formation of nonequilibrium structural-phase states in surface layer during electron-beam irradiation in submillisecond exposure time range is determined by ultra-high rates of heating (up to 10^6 K/s) of thin surface layer of material (10-4-10-3mm) to the melting point and formation of limiting gradients of temperature (up to 107 - 108 K/m), which ensure cooling of surface layer due to heat transfer to the bulk of material at 10^4 - 10^6 K/s. Compared with high power ion beams, which can also be used to modify surface of materials, low-energy (<30 keV) dense electron beams are generated with significantly higher efficiency (more than 90%) in frequency-pulse (~ $10s^{-1}$) mode with less (by an order of magnitude) accelerating voltages and do not require creation of special radiation protection as soon as the accompanying X-ray radiation is shielded by the walls of working vacuum chamber. High energy efficiency, higher homogeneity of energy density along the flow cross-section, good pulse reproducibility and high frequency of pulses advantageously distinguish pulsed electron beams from pulsed low-temperature plasma flows, for potential use of both for technological purposes. International priority in development of pulsed electron-beam devices based on plasma cathodes, including surface treatment of materials, belongs to the Institute of High Current Electronics of Siberian Branch of the Russian Academy of Sciences (ISE SB RAS). At present, the ISE SB RAS has the most up-to-date complex of research equipment for pulsed electron-beam irradiation of materials in a wide (including unexplored) range of values of irradiation parameters – “UNIKUUM” - the set of unique electrophysical installations for effective electron-ion-plasma modification of surface of materials and products. Having an international priority in development of pulsed electron-beam devices based on plasma cathodes, high professionalism, wide access to modern analytical equipment, significant amount of positive results of preliminary studies on the claimed subject, the team of project executors believes that the results obtained in the work will be original and provide novelty of the world level.

Present work will be carried out within the general direction of development of scientific research and practical developments - surface protection by spraying coatings using concentrated energy flows. The purpose of the work is formation of electroerosion-resistant coatings by electrospray coating method and subsequent electron-beam mixing (including using nitriding electroexplosive coatings to form nitrides to harden the surface coating layer), to study their structure, phase composition and properties. Coatings will be investigated using the following equipment: optical microscope, scanning electron microscope, transmission electron microscope, X-ray diffractometer, optical interferometer. Coatings for wear resistance and electroerosion resistance, nanohardness and Young's modulus will be tested. As a result of the project, physical nature of formation of structure and properties of electroexplosive electro-erosion-resistant composite coatings of Ag-Ni, Ag-Cd, Ag-C and Ag-Co systems will be established after electron-beam mixing, including nitriding of electric explosive coatings. The results obtained in this project will serve as a stimulus for further research in the field of electric explosive spraying and electron-beam mixing of electroerosion-resistant coatings.

* The present work was performed within Russian Science Foundation project No. 19-79-20007.

SYNTHESIS OF C-N POWDER MATERIALS BY ARC DISCHARGE PLASMA*

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Carbon nitride C_3N_4 is binary compound of carbon and nitrogen. There are seven different phases of C_3N_4: α - C_3N_4, β - C_3N_4, cubic C_3N_4, pseudocubic C_3N_4, g-h-triazine, g-h-heptazine and g-o-triazine. Among them, β - C_3N_4 crystalline phase has similar hardness/low compressibility to that of diamond. However, today more and more attention is paid to the hexagonal or so-called graphite-like carbon nitride h-C_3N_4 (g-C_3N_4) [1]. This material are currently being studied for a wide range of applications, such as main catalyst in hydrogen photocatalysis [2], as a coating for implants in biomedicine [3], as a precursor for synthesis of superhard phases of C-N system [4].

One of the methods to obtain the g-C_3N_4 is electric arc discharge method [5,6]. Today this method is developing in the direction of vacuumless synthesis. In this regard, an attempt to synthesize crystalline C-N powder materials by atmospheric arc discharge plasma has been done.

Figure 1 shows typical current and voltage waveforms taken by oscilloscope during the experiment.

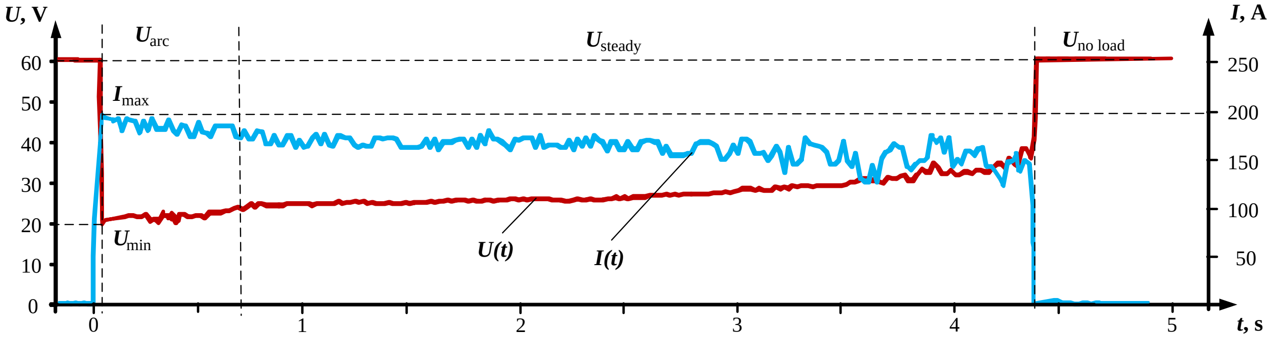

Fig. 1. Typical current and voltage waveforms taken during the experiment

As it can be seen from the fig.1, at the initial time voltage on the electrodes is equal to the no-load voltage of the power supply U ≈ 60 V, the discharge circuit current is zero. Then, at the moment of discharge initiation, the voltage drops to the minimum value of U ≈ 20 V, respectively, the current increases to the maximum value of I ≈ 200 A. After the discharge gap is formed, the voltage and current of the system stabilize to steady-state values U ≈ 30 V and I ≈ 160 A, respectively. After the end of the arc discharge, at the time t = 4.4 s, the current value drops to zero, the voltage is restored to its initial value, equal to U ≈ 60 V. It should be noticed that in the time interval from 0.1 s. to 4.4 s. the voltage increases by ΔU ≈ 8 V. This is explained by anode evaporation, therefore, anode length decreases, and the discharge gap size increases.

Based on the data from Fig. 1, the dependences of power and energy on time were obtained. Power is maintained in the range of 0.2-4.4 s. Moreover, the P(t) waveform is similar to the I(t). The average power is equal to 4 kW during the experiment. In turn, the power provides energy release in the system, equal to 21 kJ for 4.4 s.

Thus, in this paper, the changing of experiment parameters, such as arc current, voltage, power and energy, obtained during the synthesis of C-N powder materials, was analyzed.

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CHARACTERIZATION OF THE α-Al_2O_3 COATINGS DEPOSITED BY REACTIVE EVAPORATION IN ANODIC ARC UNDER HIGH-CURRENT ION ASSISTANCE*

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Reactive anodic evaporation of Al in a discharge with a self-heating hollow cathode provides high (~ 4.5 μm/h) deposition rates of Al_2O_3 coatings. For the crystallization of coatings during the deposition process at a low temperature, intensive ion assistance [1] is necessary, moreover for the formation of the α-phase of Al_2O_3 the ion energy must be within the narrow range [2].

Stable growth of the α-phase at 640 °C was ensured by using low-energy (~ 50 eV) high-current (up to 15 mA/cm^2) ion assistance under conditions of reduced degree of ionization of evaporated Al and increased degree of oxygen dissociation. To increase the ion current density and the degree of oxygen dissociation, a hollow anode was used parallel with the anode-crucible. An oxygen flow and a large part (up to 36 A) of the electron current pass through the hollow anode aperture thus ensures the effective interaction of oxygen with energetic electrons.

α-Al_2O_3 coatings were obtained, which are characterized by the presence of a dense surface layer with a structure corresponding to zone 3 of the Thornton diagram [3] and the underlying column layer (Fig. 1). The structural-phase state of the Al_2O_3 coatings, their adhesive strength and surface roughness were investigated.

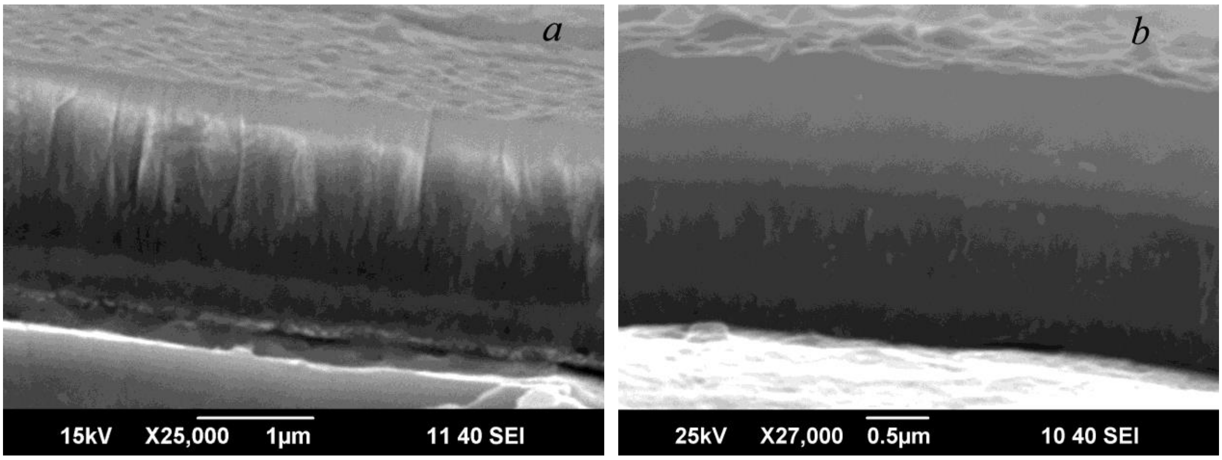

Fig. 1. Images of the brittle cleavage of Al_2O_3 coatings deposited at different currents to the hollow anode: 4 (a) and 28 A (b).

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HIGH-RATE LOW-TEMPERATURE PVD OF THICK (10 μm) α-ALUMINA COATINGS *

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The method of anodic evaporation of Al in Ar-O_2 medium and deposition under intense ion assistance allows control of evaporation rate of metal, plasma density and composition, current density and energy of ions on the surface of the growing coating independently [1, 2]. These features of the method were used to reduce the crystallization temperature of Al_2O_3 coatings to 640 °C and the intrinsic stresses in the coating. An increase in the deposition rate of the coating was achieved by optimization of the ratio of atomic fluxes of Al and O on the surface of the growing coating. Single-phase adhesive α-Al_2O_3 coatings ~10 μm thick with a hardness of ~20 GPa and a Young's modulus of ~260 GPa were obtained.

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MODIFICATION OF THE SURFACE STRUCTURE OF STEEL BY COMBINED ELECTRON-PLASMA METHOD

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One of the promising technologies for hardening surface layers and hardening protective coatings of metals and alloys is based on the use of surface modification, combining plasma spraying of a powder coating and the subsequent irradiation with an intense pulsed electron beam. The use of surface modification of materials that combines formation of a molten layer on the surface of a material by plasma treatment and the simultaneous introduction of powders into this layer and the subsequent irradiation of the formed protective coating with an electron beam is a promising direction.

The purpose of the paper is to study the tribological properties of the modified surface layer on a steel substrate formed by plasma spraying of a powder of the Ni-Cr-B-Si system and the subsequent irradiation with a high-energy pulsed beam.

Surface modification of A3 steel (United Kingdom marking) was carried out by plasma spraying of Ni-Cr-B-Si powder onto a steel surface using an original installation equipped with two plasma generators [1]. Further, the surface was irradiated with an intense pulsed electron beam on the installation SOLO.

Tribological testing of samples was performed using the “Tribotechnic” tribometer. The test process was carried out at a load of 1÷2 H according to the “finger-disk” scheme under dry friction conditions. The tests were carried out outdoor. Testing time was up to 1000 sec. Images of wear marks were taken using the Axiovert 40 MAT optical microscope (Figura).

The analysis of tribological tests data have allowed establishing that electron beam processing with a capacity of 40 J/cm^2 leads to a decrease in the sample wear resistance and the appearance of the fatigue spalling process along with normal mechanochemical wear. Lower capacity of the electron-beam effect of 20 J/cm^2 allows increasing the wear resistance of the material, as compared to the initial state. From the tests performed, it can be concluded that excessive surface hardening with the combined effect of plasma coating deposition and high-power electron-beam processing reduces wear resistance, as compared to untreated samples and samples processed at lower capacity.

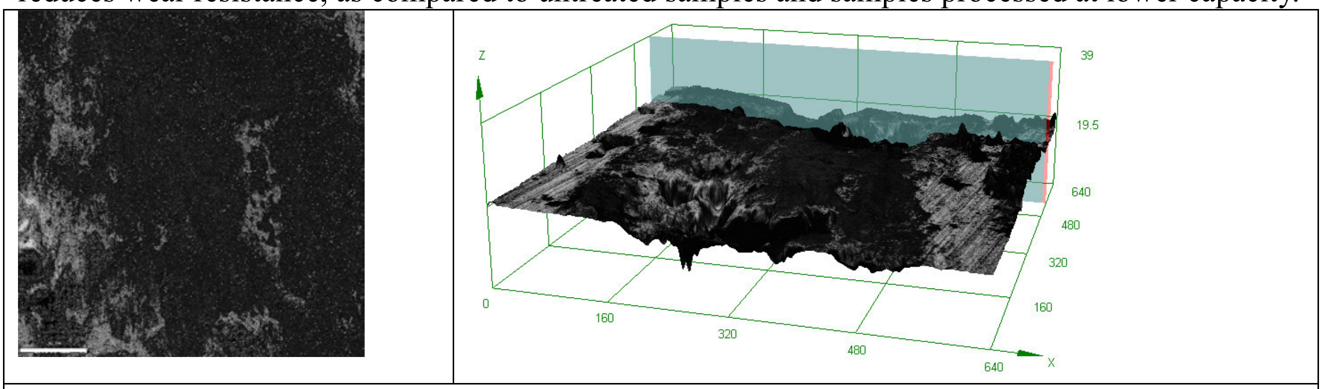

Fig. The section of the friction track on the surface of the steel sample after plasma spraying of the powder of the Ni-Cr-B-Si system and irradiation with an electron beam of 20 J/cm^2 (*a*). The profilogram of the cross section of the friction track (*b*).

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INFLUENCE OF METAL-GAS PLASMA COMPOSITION AND PARAMETERS ON COMPOSITION AND CHARACTERISTICS OF NITRIDE COATINGS *

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Generation of gas-metal plasma for vacuum arc plasma-assisted deposition of coatings was carried out by plasma sources of different type: 1) arc evaporator with magnetic filtration of a plasma flow and source of gas-discharge plasma with the combined thermionic and hollow cathode on the ion-plasma QUINTA installation [1, 2]. Zirconium alloy (Zr-1%Nb, E110) was used as material of the evaporated cathode. Generation of gas-metal plasma and coating deposition were carried out in mixture of Ar-N_2 gases, the partial pressure of nitrogen changed in the range of 0.01-0.2 Pa at total mixture pressure of 0.2 Pa. In the plasma-assisted modes at constant working pressure and constant arc current of evaporator arc current of gas plasma source was changed in the range of 10 to 150 A.

Parameters of gas, metal and gas-metal plasma were measured by a single cylindrical Langmuir probe and the automated system of probe measurements [3]. The composition of plasma was analyzed on the radiation lines obtained by a spectrometer method in several ranges of wave lengths. Change of coatings composition at variation of plasma parameters and composition was investigated on a scanning electron microscope (Philips SEM-515 with the EDAX ECON IV microanalyzer). Micro- and nanohardness were measured on the PMT-3 microhardness tester (LOMO, Russia) and DUH-211S nanohardness tester (Shimadzu, Japan), respectively. The structure and phase composition were investigated by X-ray diffraction analysis (Shimadzu XRD 6000 diffractometer) and transmission electron microscopy (JEOL JEM-2100 F). Tribological characteristics were measured on a TRIBOtester of Pin on Disc and Oscillating (TRIBOtechnic, France).

Influence of composition and parameters of plasma on elemental and phase composition, structure and characteristics of coatings based on ZrN was revealed. The optimum synthesis modes for these coatings with high wear resistance were revealed.

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VACUUM ARC DEPOSITION OF MON COATINGS IN THE MODES OF PLASMA ASSISTENCE*

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In the modern industry, functional coatings are actively introduced to increase the strength characteristics of various products. Nitrides of many kinds of metals have found wide application. At present titanium nitride (TiN) and coatings based on it (e.g., TiAlN, TiCuN and etc.), are widely used [1]. The coatings based on molybdenum nitride (MoN) have great prospects in industry due to its high hardness, low friction coefficient and chemical inertness to non-ferrous metals [2].

The purpose of this work is the investigations of the influence of the operating modes of the sources of gas and metal plasma on the properties and composition of molybdenum nitride coatings. A plasma generator based on a non-self-sustained arc discharge with a combined thermionic and hollow cathode "PINK-04P" was used as a source of gas plasma [3]. The source of metal plasma was an arc evaporator "DI100" with improved design. The material of the evaporated cathode was molybdenum of MCH brand.

There are results of the series of experiments on researches of the parameters and composition of gas and gas-metal plasma. A number of experiments were carried out to obtain single-layer coatings of molybdenum nitride with a thickness of 3-5 μm deposited at different parameters of arc discharges. The composition and tribological properties of the obtained coatings were investigated. The correlation between the composition of the gas mixture and the parameters of arc discharges and the composition and properties of the deposited coatings was revealed.

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IRRADIATION BY A LOW-ENERGY PULSED ELECTRON BEAM OF ZIRCONIA-BASED COMPOSITE*

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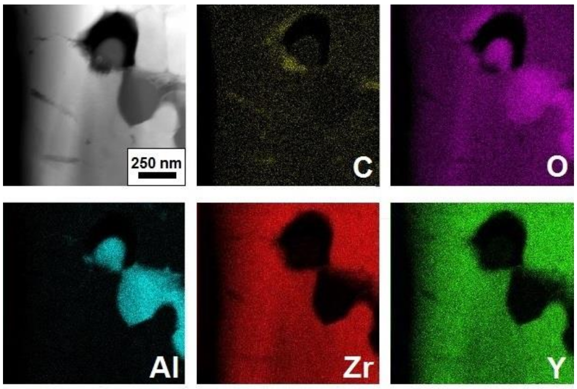
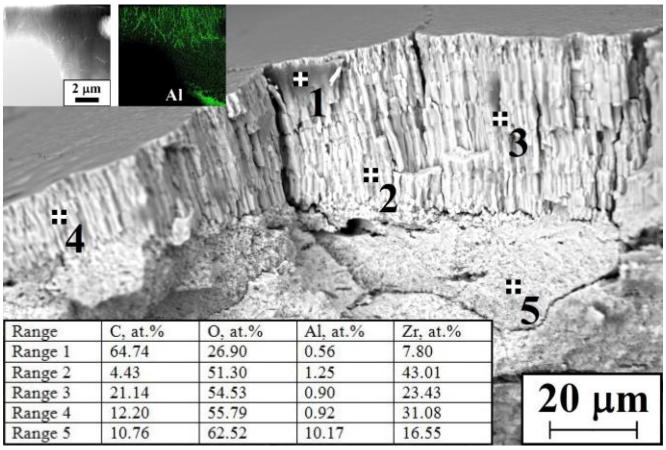
In this work, tetragonal zirconia-based composite prepared by spark plasma sintering, modified by 5 wt% alumina nanofibers and 0.5 wt% single-walled carbon nanotubes, was investigated. Similar composites were investigated in previous work [1]. Irradiation by a low-energy pulsed electron beam of the submillisecond duration was carried out on the device "SOLO" [2] in the following mode: beam energy density – 15 J/cm^2, pulse duration – 200 μs, pulses quantity – 10, 20, 30, and 40, and pulse repetition rate – 0.3 Hz.

The initial composite material (Fig. 1a) consists of ZrO_2 matrix, in which there are alumina grains of complex elongated shape and carbon nanotube bundles, which are uniformly distributed in the matrix. Such composite possesses improved mechanical properties (microhardness and fracture toughness increase by 1.4 % and 17.2 %, respectively), as compared to ZrO_2 ceramics without additions.



Element	C	O	Al	Zr	Y
at.%	13.76	49.36	7.54	26.42	2.76

(a)



Range	C, at.%	O, at.%	Al, at.%	Zr, at.%
Range 1	64.74	26.90	0.56	7.80
Range 2	4.43	51.30	1.25	43.01
Range 3	21.14	54.53	0.90	23.43
Range 4	12.20	55.79	0.92	31.08
Range 5	10.76	62.52	10.17	16.55

(b)

Fig. 1. STEM image of the sample before irradiation and element mapping of same area (a); SEM image of the cross section of composite after electron beam processing at 40 pulses. Areas are marked and numbered for which the elemental composition (table) is determined (b).

It has been established that electron beam treatment leads to the formation of modified surface, the thickness of which varies from 5–10 μm to 100 μm. Modified volume is multi-layered (Fig. 1b): the upper layer has a columnar structure; the intermediate layer between the surface layer and the base material consists of equiaxed grains with sizes from 0.5 μm to 1 μm, that more grain size (~ 0.25 μm) of the initial material.

XRD analysis showed that, the initial composite contains tetragonal modification of zirconia (t-ZrO_2) and a small amount of α-Al_2O_3. In the irradiated samples, in addition to t-ZrO_2 and α-Al_2O_3, a new compound Zr–Al–O (zirconium aluminum oxide) appears.

According to the EDS method results, Al atoms in the initial composite form Al_2O_3 nanofibers, which are preferentially, located parallel to the sample surface. In the modified layer, when irradiated by an electron beam, the Al atoms form thin interlayers along the boundaries of the columnar grains (inset in the upper left corner of Fig. 1b).

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ION-PLASMA ZR-NB-N COATINGS: EQUIPMENT, DEPOSITION AND PROPERTIES.*

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The paper presents the results of research on plasma-assisted arc deposition of the combined Zr-Nb-N coating. The mechanical characteristics of the coating and the elemental composition were investigated.

The work was performed on the KVINT ion-plasma unit developed at the laboratory of plasma emission electronics of the Institute of High Current Electronics SB RAS [1] and included in the list of unique electrophysical units of the Russian Federation (УНИКУУМ complex, http://ckp-rf.ru/usu/434216).

The sputtering was performed from two cathodes: zirconium, installed in the cathode assembly of the magnetic filter of the microdrop fraction, and niobium from the evaporator DI100. The coating was applied in two stages: first, the zirconium underlayer for 10 minutes at a discharge current of an arc evaporator of 150 A and an argon pressure of 0.2 Pa. Then a layer of Zr-Nb-N was applied with currents of arc evaporators 150 and 100 A for zirconium and niobium, respectively. The total pressure of the gas mixture (Ar: N2 - 50:50) was 0.2 Pa. The coating was applied within an hour. The samples were located in the center of the vacuum chamber on a rotating table and on a table satellite at a diameter of 300 mm rotating planetary.

Using the CaloTest method, the coating thickness was measured and the growth rate of the coating was calculated. The growth rate of the coating was 4.36 µm/h at the center of the chamber and 4.92 µm/h on the table satellite. The difference in deposition rates is explained by the directivity pattern of arc evaporators.

The hardness of the coating under a load of 1 N was about 30 GPa for both samples.

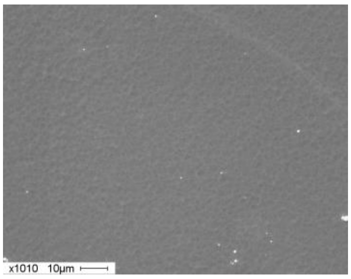

Fig. 1. SEM image of the coating surface.

Elemental composition

Таблица 1. Centre

Element	***Wt%***	***At%***
N	13,41	50,27
Zr	66,42	38,30
Nb	20,17	11,43

Таблица 2. Satellit

Element	***Wt%***	***At%***
N	14,62	52,72
Zr	64,07	35,66
Nb	21,31	11,62

The study of the elemental composition shows that the coating has an almost stoichiometric composition of nitrogen. Small differences in the ratio of zirconium and niobium are caused by the directivity pattern of arc evaporators.

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OPTIMIZATION OF PLASMA DYNAMIC SYNTHESIS PROCESS FOR INCREASING THE YIELD AND PURITY OF ε-FE_2O_3 (EPSILON) PHASE

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Iron oxides are among the most common used materials in the various fields of science and technology [1]. Among the known non-hydrated phases, the production of the epsilon phase of iron oxide (ε-Fe2O3) causes the greatest difficulties, since it is associated with the need to synthesize in a very narrow temperature range while maintaining the nanoscale state [2, 3]. This material also causes great scientific interest, since it has been established that this phase has the largest coercive force among all known simple metal oxides and is capable of absorbing electromagnetic radiation in the millimeter wavelength range [4, 5].

Earlier [6], the possibility was convincingly proved to obtain this unique iron oxide modification using a plasma dynamic synthesis method based on the use of low-temperature iron-containing plasma generated by a coaxial magnetic plasma accelerator [7, 8] and flowing into an oxygen atmosphere. The special features of the synthesis process (high plasma flow speed ~3 km/s and high cooling rate $\sim10^8$ K/s) make it possible to preserve the necessary epsilon phase during high-speed sputtering from the boundary of the head shock wave of an ultrafast plasma flow as well as to achieve an output of at least 50 wt. %

In this work, the possibility was studied to increase further the yield of the epsilon phase of iron oxide in the composition of the heterophase synthesis product. For this, key features of the process were revealed that affect the production of ε-Fe2O3, which include the need to increase the lifetime of the quasi-stationary flow regime and the energy input to the system. Taking into account these data, appropriate design and circuit solutions for the system have been implemented that make it possible to obtain iron oxide powder with an output purity of epsilon phase of at least 90 wt. %. Another advantage was found to be an increase in the mass yield of the necessary phase.

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PREPARATION OF HIGH-VOLTAGE VACUUM GAP SURFACES BY THE GLOWING DISCHARGE

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Currently, when a certain number of gas-discharge devices (GDD) are operating, failures associated with a decrease in the electrical strength of the high-voltage vacuum gap are observed. As shown in [1], one of the reasons is the emission processes on the insulator inner surface and the electrode surfaces of the high voltage gap caused, in particular, by the presence of dielectric and oxide films on them, as well as adsorbed molecular gases. The consequence of the electron emission is the irradiation of the dielectric as an electron flux and γ-quantum fluxes [2]. In this case, the GDD vacuum shell is charged [2], which contributes to the appearance of either an incomplete electric discharge on the dielectric surface or a through breakdown. Both phenomena lead to degradation of the vacuum shell and loss of tightness of the device.

The effect of residual and working gases adsorbed by the GDD internal surfaces is also manifested in the form of sorption and desorption processes [3] under the influence of corpuscular flows and thermal loads. In this case, during the operation of the device gas exchange between the parts working surfaces is observed, which contributes to the appearance of pressure surges when the GDD is turned on after long interruptions.

The literature sources analysis shows that currently in the GDD manufacture to remove oxides and sorbed gases, along with traditional methods of cleaning parts and assemblies in preparation for Assembly, additional methods are effectively used. It is based on the GDD structural elements processing in a glow discharge plasma of an inert gas environment [4]. However, the sequence and modes of processing described in the literature are largely determined by the geometric and physical characteristics of the treated parts and are individual for a particular type of device.

Therefore, in the present work, in order to improve the GDD electrical strength and stability, operating on the Penning discharge basis, a method of parts and assemblies plasma processing was implemented at the stage of their preliminary preparation for product assembly. Figure 1a shows a photograph of the discharge realized when high-voltage vacuum gap electrodes are processing. Figure 1b shows a photograph of the discharge realized when treating the inner surfaces of high-voltage vacuum gap insulator.

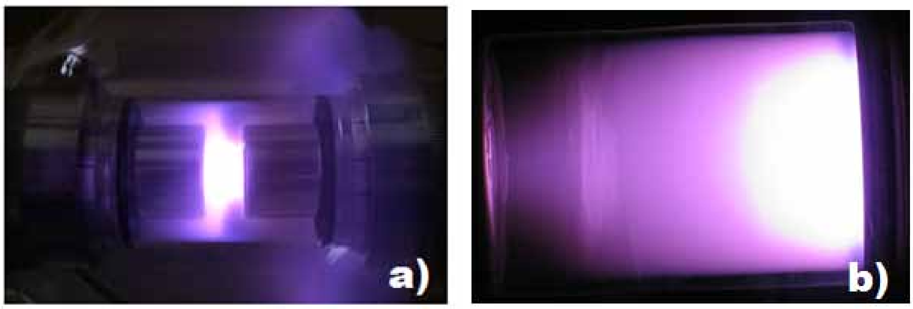

Fig. 1. Photograph of the discharge realized when high-voltage vacuum gap electrodes are processing (a) and when treating the inner surfaces of high-voltage vacuum gap insulator (b)

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EXPERIMENTAL AND NUMERICAL STUDY OF HIGH-TEMPERATURE SYNTHESIS OF NANOSIZED SILICA PARTICLES IN FLOW-TYPE PLASMACHEMICAL REACTOR*

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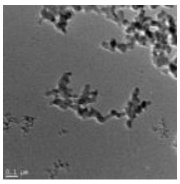
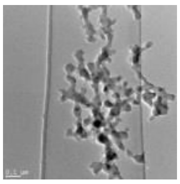
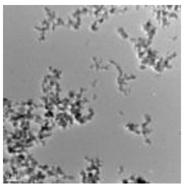
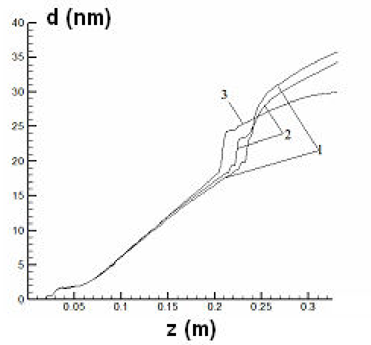
Nanosized silica powder is commonly used in variety of technologies, namely, in solar energy conversion, as ingredient for polishing slurries in optoelectronics, in photo-catalysis, as an adsorbing agent, as a catalyst support as well as reinforcing filler for rubbers and plastic materials, etc. [1]. Based on devised pilot lab set-up the results of experimental study of synthesis of samples of nanosized silica powders obtained by one-step chloride method have been presented in [2]. One of the most essential challenges of plasma-chemical synthesis of ceramic nanopowders is how to improve control of their physico-chemical properties at the stage of particle formation and its further growth. The control of depth of counter flow jet quenching determined by ratio of momentum-flux of cold jets to that of high-temperature flow with synthesized particles enables one to solve largely this problem. In this work given operating parameters of the set-up the morphology and properties of the samples of silica powder obtained at different mass flow rates of quenching air jets have been analyzed. Using acquired experimental data as feedback information the parameters of corresponding numerical model of the synthesis have been more precisely specified to solve this inverse problem. This would allow one to predict sizes of particles being synthesized with sufficient accuracy. Below the results of analysis of silica powder samples as well as predictions of conversion of SiCl4 to SiO2 nanoparticles are demonstrated.

Morphology and physico-chemical properties of silica powder samples synthesized in accordance with overall reaction

$SiCl_4 + O_2 \rightarrow SiO_2 + 2Cl_2$

Mass flow rate of quenching air jets, g/s	1.8	4.1	8.1
Specific surface area of silica powder sample S_{BET}, m^2/g	70	73	96
Particle average size evaluated based on S_{BET}, nm	39	37.4	28.4
Molar fraction of contaminating chlorine, atom.%	0.38	0.12	0.13
Photo of silica powder sample			

Cross-section mass average particle diameter distribution along the reactor for mass flow rates of quenching air jets: 1 – 1.8 g/s, 2 – 4.1 g/s, 3 – 8.1 g/s



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SURFACE TREATMENT OF METALS, DIELECTRICS AND SEMICONDUCTORS BY RUNAWAY ELECTRON PREIONIZED DIFFUSE DISCHARGE*

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In recent years, atmospheric pressure diffuse discharges are actively being studied by scientific collectives. Plasma of such diffuse discharges can be used for modification and improvement surface properties of various materials and can be used for thin film deposition processes, in medicine, micro- and nanoelectronics etc.

This paper deals with experimental results focused on surface treatment of metals (Cu, Nb, Ti, Al, St3), dielectrics (polyimides, polysulphones, organosilicon films) and semiconductors (silicon, CdHgTe) by runaway electron preionized diffuse discharge (REP DD) plasma at atmospheric pressure.

Elemental composition, roughness, surface free energy, nanohardness and surface structure were studied for metals surface after treatment by REP DD. Experimental results shows that surface of treated metals becomes ultrafine cleaned from carbon-like bandings. Also, REP DD treatment of metals result in 3-times increasing of surface free energy, smoothing and structural changes of near-surface layer [1].

In a case of surface treatment of dielectric such as polyimides and polysulphones it is shown by IR-spectroscopy methods that these materials have high resistant to the electron beam irradiation as well as REP DD plasma treatment. Such a properties provide an opportunity of using these materials in space to protect spacecraft crew from cosmic radiation [2].

Besides of that, surface treatment of CdHgTe (CMT) epitaxial films by atmospheric pressure REP DD is studied in this work. It is shown that irradiation of nanosecond diffuse discharge on the CMT surface leads to the changing of electrophysical properties of CMT as a result of formation of near-surface high-conductivity layer with n-type conduction [3].

Thus, surface treatment of metals, dielectrics and semiconductors by runaway electron preionized diffuse discharge can be used for surface cleaning, activation, increasing of adhesive properties, changing of structural and electrophysical properties. Also, REP DD treatment provides controlled changing of CMT epitaxial films properties and producing of structures with heterogeneous conductivity.

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REDOX PROCESSES INVOLVING CHROMIUM IONS, INITIATED BY THE ACTION OF A DISCHARGE IN AIR, OXYGEN AND ARGON ON AQUEOUS SOLUTIONS

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Industrial plants involved in metal finishing, leather tanning, textile finishing and plating are the source of wastewater pollutions with chromium ions. Chromium exists in water solution in two stable forms with the oxidation level of +6 (Cr^{6+}) and +3 (Cr^{3+}). Cr^{3+} is less harmful while Cr^{6+} is a strong toxicant, mutagen and carcinogen. For these reasons, the maximum permissible concentration of Cr^{6+}in water is markedly lower than that of Cr^{3+}. Chemical Cr^{6+}reduction is the most used method for transformation of Cr^{6+} to Cr^{3+}. For this, ferrous sulfate, sodium sulfite, or sodium metabisulfite are applied as reducers. In spite of these methods being rather effective, they require an application of the reducer in excess due to the reversibility of the reduction process which becomes a source of additional water contamination. In the case of sodium sulfite and sodium metabisulfite, harmful gaseous sulfur oxide (IV) is formed. It is known that the action of discharges at atmospheric pressure maintained above water surface or in water bulk results in the formation of reactive oxygen species in a liquid phase such as H_2O_2, O_2 molecules, •H, •OH, HO_2• radicals and many others. Depending on the conditions, these particles can play the role of oxidants or reducers in relation to chromium ions. The advantages of discharge systems are obvious. They do not need any chemicals and their action does not result in the formation of harmful products.

For these reasons the process of reduction of Cr^{6+} ions (water solution of potassium dichromate, $K_2Cr_2O_7$) in a water cathode was studied during a DC discharge in air, Ar and O_2. The concentration range of Cr^{6+} was (5.7-19)×10^{-5} mol/l and discharge current range was 20-80 mA. The photometric method was used to determine the concentration of Cr^{6+} and Cr^{3+}. For the plasma the electric field strength, and the cathode voltage drop$_c$, voltage drop between anode and cathode was measured as well.

For all gases under study Cr^{6+} ions were shown to be reversibly reduced under a discharge action. The equilibrium degree of reduction increased with increasing initial concentration of the solution at fixed discharge current. At fixed initial concentration the reduction degree increased with increasing discharge current. The reduction degrees so obtained were 0.34-0.84. On the basis of kinetic measurements, the effective rate constants for the oxidation and reduction of Cr^{6+} and Cr^{3+} ions were determined. For the discharge in air, argon and oxygen for a concentration of 0.1 mmol/l and a current of 40 mA, the reduction rate constants were $(4 \pm 0.7) \times 10^{-3}$, $(1.1 \pm 0.2) \times 10^{-2}$, and $(2 \pm 0.4) \times 10^{-3}$ s^{-1}, respectively. Calculations for a discharge current of 40 mA and a concentration of 0.1 mmol / l gave the following values of the energy efficiencies for the reduction of Cr^{6+} ions: argon - 4.2×10^{-2} ions per 100 eV of inputted energy; oxygen - 2.9×10^{-3}; air - 0.75×10^{-3}. Despite the fact that the discharge in air demonstrates higher constants of the reduction rates than the discharge in oxygen, the energy efficiency of the discharge in oxygen turns out to be higher. The reason is that in order to maintain the same current, the discharge in the air requires high power.

A kinetic scheme of the processes taking place in a solution was proposed. The scheme included 52 reactions involving chromium ions and H_2O_2, •OH, •H, solvated electrons, H_2, O_2, H^+, OH^-, HO_2•, O_2^-, HO_2^- ,O^-, and O_2^{2-}.The calculated data obtained as a result of application of this scheme described well the experimental results on Cr^{6+} kinetics. The main processes of Cr^{6+} reduction and Cr^{3+} oxidation were revealed. HO_2• radicals and hydrogen peroxide were shown to be responsible for Cr^{6+} reduction whereas •OH radicals and O_2 molecules provide the reverse process of Cr^{3+} oxidation to Cr^{6+}. The mechanism of action of phenol additives improving the process efficiency is discussed. The efficiency of phenol action as a radical scavenger was shown to be determined with its mass-transfer to the reaction area rather than chemical reaction rate.

This study was carried out in the frame of Project part of State Assignment of the Ministry of Education and Science of the RF, No 3.1371.2017/4.6.

SYNTHESIS OF NI-AL INTERMETALLIC SURFACE ALLOYS PRODUCED BY USING A LOW-ENERGY HIGH-CURRENT ELECTRON BEAM

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Carbon steels are widely used in various applications, however their wear resistance, corrosion and oxidation resistance are weak. To improve these properties, methods of surface engineering can be used. One of the most commonly used coatings for steel is Ni-Al compounds [1]. The intermetallic Ni-Al compounds give a combination of high strength and hardness, resistance to fatigue and creep, good corrosion and oxidation resistance at high temperatures [2,3]. Therefore, they are considered as promising materials of protective coatings for industrial metals and alloys for high-temperature applications and aggressive environment which can enhance the performance and stability of catalysts, turbine blades, ferroelectric capacitors, vanes and so on [4,5].

However, there are some difficulties in producing intermetallic NiAl coatings using traditional coating technology: unsatisfactory adhesion properties, complex surface geometry. One of the methods that can be effectively applied to the manufacture of Ni-Al coatings is the method of forming surface alloys.

The aim of present work was to synthesize of Ni-Al surface alloy directly on steel substrate in vacuum using magnetron deposition of Ni and Al layers and consequent irradiation with a low-energy, high-current electron beam.

The electron-beam machine “RITM-SP” with an explosive-emission cathode and a plasma-filled diode generating the LEHCEB was employed in the work [6]. This machine is equipped with a multi-magnetron sputtering system enabling formation of multicomponent surface alloys. The surface alloy was synthesized of 2.5 µm thick. It is known that depending on the atomic ratio characterized by Al and Ni layer thicknesses, Al_3Ni_2, Al_3Ni or NiAl can be formed as the final product. In this work, the emphasis was down to a constituent of the equiatomic composition NiAl. Three types of multilayer systems were deposited for surface alloy formation: 3-layer system Ni (0.5 µm) –Al (1.52 µm) –Ni (0.5 µm) (*1*); 9-layer system Ni (110 nm)– Al (167 nm)– …– Ni (110 nm) (*2*); 2-layer system Al (167 nm) – Ni (110 nm) deposited 9 times (*3*) followed by LEHCEB irradiation after each deposition.

The surface morphology, phase and elemental composition of the Ni-Al surface alloys were analyzed, the microhardness and wear resistance were measured. For characterization different techniques like SEM, XRD and others have been used. The elemental composition of both the surface and cross sections of the samples was analyzed by EDS analysis. The structure and properties of the synthesized Ni-Al surface alloys were compared with witness-specimens, which were three types of multilayer systems without LEHCEB treatment.

Figure 1 shows the images of the Ni-Al surface alloy formed for three types of multilayer systems. It can be seen that the synthesis of a surface alloy by nanolayers of Ni and Al deposition leads to cracking of the surface due to the formation of brittle Al_3Ni and Al_3Ni_2 phases.

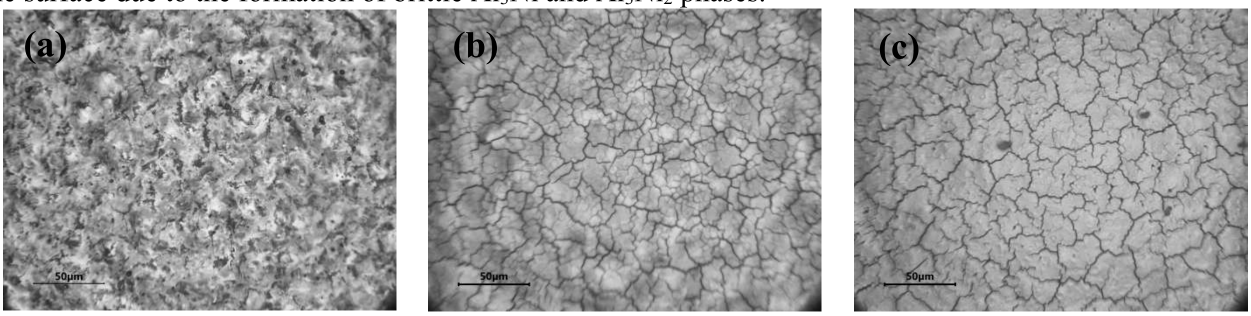

Fig. 1. The surface of the synthesized Ni-Al surface alloy for different types of multilayer system: *1* (a); *2* (b); *3* (c).

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ROUGHTNESS OF NICKEL AND TITATIUM ULTRATHIN FILMS COATED BY MAGNETRON SPUTTERING TECHIQUE

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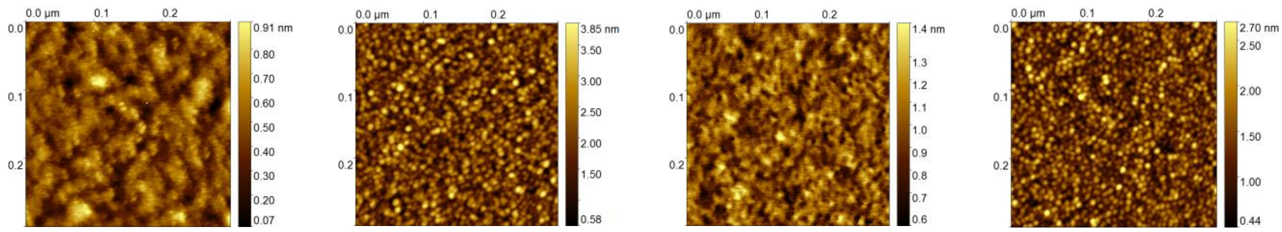
Ultrathin nickel and titanium films (up to 50 nm) are interesting as the basis for the multilayer coatings for the neutron optics mirrors [1]. Also it may be used as alternative technology of ITO coatings for transparent electrodes production [2]. In contrast the others materials (copper and silver) there is insufficient attention was paid to Ni and Ti ultrathin films technology. Also the most of articles is devoted to films obtained in laboratories and which are not applicable in industrial. The investigation of the influence of different parameters (magnetron discharge power Q, substrate temperature T_s and discharge gas pressure P_d) of ultrathin Ni and Ti coatings process to the film roughness in industry is the goal of this work.

The work was carried out at industrial magnetron facility. The films were coated with the industrial magnetron sputtering systems on the K8 optical glass substrates with argon environment. The magnetron power was from 200 to 1500 W when titanium film coating. When nickel film coating the power was from 200 to 1000 W. The substrates temperature was from 20 (room temperature) to 200 ^oC. The films were coated at discharge gas pressure was $8.2 \cdot 10^{-2}$ to $3.1 \cdot 10^{-1}$ Pa. The coatings thickness was 10±1 nm. The film thickness and roughness were measured with atomic-force microscope (AFM).

It was determined that all the parameters are influence the coatings roughness. The smallest roughness of titanium coatings (Rq = 0.13±0.05 nm) was obtained at $P_d = 8.2 \cdot 10^{-2}$ Pa, T_s = 200 ^oC, Q = 1500 W. Nickel coatings with smallest roughness (Rq = 0.15±0.05 nm) was obtained at $P_d = 8.2 \cdot 10^{-2}$ Pa, T_s = 100 ^oC, Q = 1000 W. The coatings with maximum roughness (Rq = 0.54±0.05 nm and Rq = 0.38±0.05 nm for Ti and Ni respectively) was found at $P_d = 3.1 \cdot 10^{-1}$ Pa, T_s = 100 ^oC, Q = 200 W for booth materials. One needs to note that nickel coatings are smoother than titanium except for some experimental points.



(a): Ti, $P_d = 8.2 \cdot 10^{-2}$ Pa, T_s = 200 ^oC, Q = 1500 W

(b): Ti, $P_d = 3.1 \cdot 10^{-1}$ Pa, T_s = 100 ^oC, Q = 200 W

(c): Ni, $P_d = 8.2 \cdot 10^{-2}$ Pa, T_s = 100 ^oC, Q = 1000 W

(d): Ni, $P_d = 3.1 \cdot 10^{-1}$ Pa, T_s = 100 ^oC, Q = 200 W

Fig 1. AFM images of the Ti and Ni coatings surfaces with smallest (*a* and *c*) and biggest (*b* and *d*) roughness

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SYNTHESIS AND PROCESSING OF POWDER MATERIALS IN DC ARC THERMAL PLASMA*

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The presentation summarizes the results of the research of the DC arc plasma jet processes that led to the creation of physical and chemical bases of the thermal plasma processes, providing production of powder materials with proper chemical and phase composition, including nanopowders and spherical particles in the micron size range.

It identified a number of promising applications of plasma synthesis of various nanopowders, including production of metal nanopowders (Ag, Cu, Ni, Co, W, Mo, Re), compounds (oxides, nitrides, carbides) and composites (W-C, W-Ni-Fe, W-Cu, Ag-SnO_2, Ni-TiCN) for various applications. As a result of the studies performed, ranges of possible variations in the physicochemical properties of powders obtained in plasma processes are established. Process parameters that control the change of these properties are defined.

The possibility of plasma spheroidization of a broad class of metal and alloy powders for additive technologies is shown.

Nowadays, IMET RAS is one of the leading organization in Russian Federation where the active researches and developments of processes and the equipment for spherical powders production of various materials in thermal plasma flow, including metals (Ti, Fe, Ni, W, Mo), alloys (stainless steel, Ti-V-Al, W-Ni-Fe, Nb-Si, Nb-C, Ni-Al, Ti-Al) and nanostructural metal-matrix composites.

As a result of studies performed, the possibility of metal powders spheroidization is shown for irregular particles shape of metals and alloys produced by various methods.

Particular attention is paid to the design of plasma process equipment and technological scheme, because, as it has been convincingly demonstrated on a commercial scale, the correct choice of raw material, the desired product, the design and equipment provides production of disperse systems in compliance with the environmental requirements and saving energy and resources.

For working and development of plasma processes of synthesis and production of pilot batches has been developed the original multifunctional plasma setup. The basic structural elements of this setup provide the necessary scaling to industrial production of broad range of nanopowders and spherical particles in the micron size range.

The results of research and development demonstrated broad possibilities of plasma processes and apparatuses based on DC plasma torches for producing nanopowders of metals and their various inorganic compounds and composites with desired properties. Nanopowders produced in plasma systems were used in a large number of research and development to prepare novel materials with special and improved properties.

Apart from nanopowders production, plasma reactors based on DC plasma torches enable spheroidization of metal and alloy powders to be used in additive technologies.

Accumulated experience forms the basis for the development of efficient industrial production of powders using plasma reactors on the basis of electric arc plasma torch.

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EHD cell parameters and collector effective area

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In recent years, an increasing interest in the development of methods for electro-hydrodynamic (EHD) control of gas flows has manifested itself throughout the world [1, 2]. Atmospheric airflow EHD devices consist of a plasma source, a drift region (acceleration block) and ion collector or neutralizer [5]. Often these three parts are united in one and form an EHD cell. The optimization of an EHD cell can significantly affect its efficiency, weight, and thrust [3, 4, 6]. In this paper, we investigated the effect of the collector electrode equivalent surface area (and the associated collector mass) on the thrust characteristics of the system consisting of five parallel cells. At the same time, the perimeter of the receiving electrode changed, and the length of the collector remained unchanged.

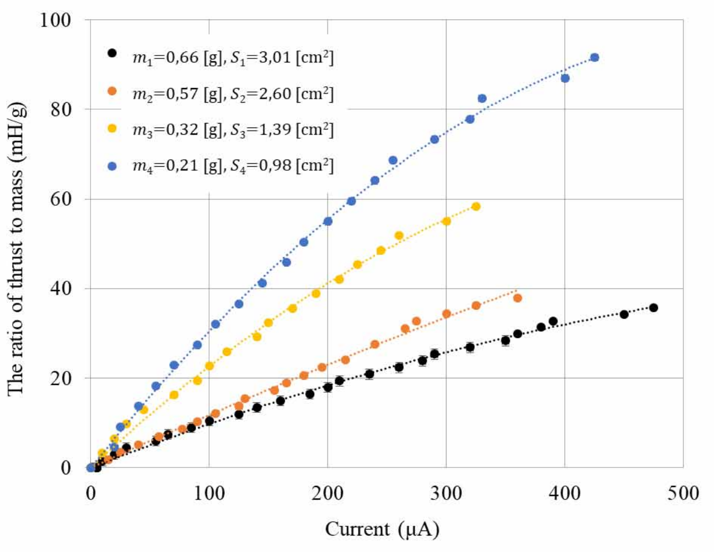

Fig. 1. The ratio of thrust to mass of collectors from on the current at different perimeters of the collectors.

The experimental setup consist of high-voltage power supply, 100 kΩ current-limiting resistor; voltmeter; EHD cell; screen; balance; microammeter. The system parameters of the EHD cell are: emitter radius $r_w = 0.04$ mm; collector radius $r_c = 0.8$ mm; interelectrode height $H = 18$ mm; intercollector distance $l_1 = 10$ mm; collector length $l_2 = 135.3 \pm 0.1$ mm; number of collectors $n = 6$. Experiments have shown that for a given geometry with closely spaced electrodes, maximum thrust is achieved at a positive corona for all values of emitter surface areas, and a decrease in the collector mass does not significantly effect on T. From the results presented in Figure 1, it can be seen that the specific thrust (the ratio of thrust to mass of collectors) per unit length increases with a decrease in their perimeter and, accordingly, the effective collector area. With a value of $I = 250$ μA, the developed lift force is more than 60 times greater than the mass of the electrode system. The use of collectors with smaller perimeters leads to gain in payload.

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MODIFICATION OF DENTURE POLYMERS IN RF-DISCHARGE AND HYBRID PLASMAS: ADVANCED TECHIQUE FOR CLINICAL PRACTICE

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Modification of hot curing poly(methyl methacrylate) (PMMA) denture base “Villacryl H Plus” in slow RF-plasma flows for material biocompatibility improvement is described. The capacitive RF-discharge was ignited in molecular oxygen by co-axial or planar electrode systems fed by generator Genesis GHW-12 (MKS Instruments, UK) at frequency 13.56 MHz. An electron beam (EB) could be injection into the space between electrodes; in this case so-called Hybrid Plasma (HP) was excited by joint action of the gas discharge and EB. Oxygen was blown in a zone of the plasma generation and samples to be treated were located directly in this zone. Special plasma chemical reactor [1] equipped with reaction chambers of various design (electrode configurations, gas nozzles, sample holders, EB modulator (optionally), etc) was developed to study materials modification under wide range of the processing conditions. As to PMMA the optimal treatment conditions were found to be as follows:

- RF-power –10-50 W depending on samples sizes;
- O_2 pressure in the working chamber– 670 Pa;
- O_2 flow – 5 sccm (standard $cm^3 \times min^{-1}$);
- accelerating voltage of the EB – 30 kV;
- EB current – 1-10 mA depending on the EB injection mode (continuous or interrupted injection were possible and various types of the EB scanning over the reaction zone could be applied).

The EB modulation and scanning supported uniformity of the sample surface modification and acceptable sample heating during the processing. In our experiments the treatment duration was varied but usually did not exceed 5 min to obtain desirable modification effect.

Experiments showed the plasma processing to result in increase in surface roughness of PMMA and change samples wettability. Significant increase of oxygen content and formation of additional oxygen containing polar chemical groups (C=O, –COOH, –OH) was also found.

Plasma chemical action on the PMMA decreased the water contact angles on modified surfaces by 1.5-2.5 times with respect to original ones and their surface free energy increased up to 1.5 times. In spite of gradual ageing, higher wettability of processed PMMA was observed at least after 7-day storage. Though both the HP and gas-discharge plasmas improve the PMMA wettability in approximately equal degree the HP gives more uniform treatment and the acquired hydrophilicity degraded significantly slower than in case of RF-plasma processing.

The biological tests on the human fibroblasts culture revealed the increased cell adhesion to the plasma-modified PMMA plates in comparison with original ones. The plasma processing also stimulated the cells growth on PMMA samples, i.e. improved the material biocompatibility.

The technique was tested on removable PMMA denture widely used in clinical practice for oral orthopedic rehabilitation of a patient after the treatment of buccal mucosa cancer. When using the non-modified denture, the patient complained of discomfort and food chewing problems and the hypertrophic red flat oral lichen formed at the patient’s cheek. The full regression of lichen nodules and associated inflammation was observed after the usage of the plasma modified denture for one week. Within six-month ware of the plasma modified denture no pathological elements or neoplasms were found on the patients’ oral mucosa [2].

Thus, the results of our study demonstrate that hot curing PMMA processed in RF- and Hybrid plasmas of oxygen can be effectively used in practical clinical dentistry.

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FORMATION OF THE SILICON COATING ON THE NITI SUBSTRATE BY MAGNETRON SPUTTERING[i]

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This study considers the possibility of using silicon as a coating on a NiTi vascular stent. It is assumed that the porous structure will be obtained on this coating in the future. In turn, it will serve as a carrier for the drug. Silicon is one of the most common material in the nature. Because of its spread, easy obtaining, thermophysical, electrophysical and chemical properties, there is an advantage to use the silicon coating in various fields of science, medicine and technics [1].

At this study, the research of structure and properties of a silicon cover was conducted. The silicon cover was gained on the NiTi substrate by using the magnetron sputtering. NiTi containing 50.9 at. % nickel was chosen as a substrate because of the use this material for making cardiovascular implants. Silicon targets of 99.999 % purity were used for silicon coating. Deposition of Si on the NiTi substrate was performed by RF-magnetron sputtering. Argon was used as an inert gas. During the coating deposition, the working pressure in the vacuum chamber was 0.7 Pa. The distance between the target of cathode and the condensable surface on the NiTi substrate was 70 mm. The treatment was conducted for the creation of surface with diverse thicknesses by the using of different modes: mode I (P=250 W; t=120 min); mode II (P=250 W; t=15 min); mode III (P=150 W; t=15 min); mode IV (P=100 W; t=15 min). An electron microprobe (EMP) was performed for the study of coated samples (Fig. 1 a), microhardness was studied as well (Fig. 1 b).

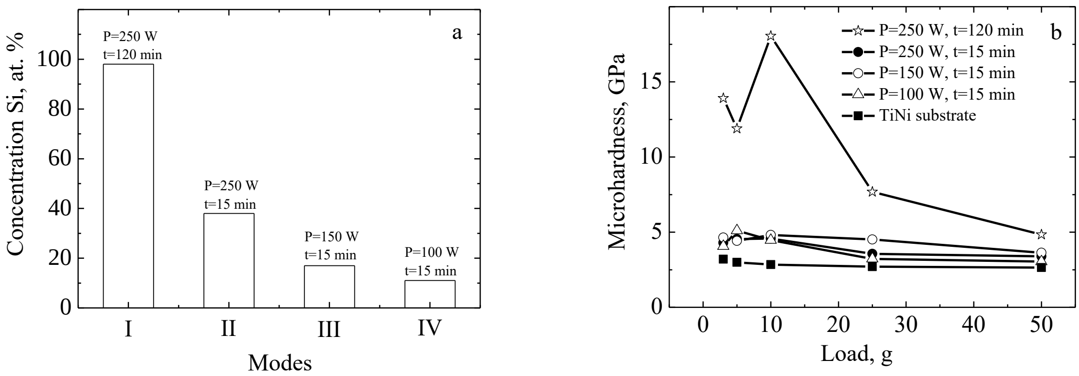

Fig. 1. The concentration of silicon in the surface layer of samples depending on the mode of sputtering (a); the microhardness of modified samples depending on the value of indenting load (b).

Microhardness was measured with various loads from 3 to 50 g. The analysis of results shows that the thickness of obtaining covers depends on the modes. It is noticed that due to the concentration of silicon in samples' surface layers. The area of X-ray generation in EMP does not exceed a depth of 5 µm for silicon. It means that the surface layer obtained in mode I with the silicon concentration of 98 at. % has comparable thickness of 5 µm. Such thickness is enough for creation of porous structure for the carrying of drug. The value of load defines the depth of dent and describes mechanical properties. It is supposed that the surface obtained by mode I has the biggest thickness and microhardness similar to silicon. Other samples have microhardness similar to NiTi. It means that the dent depth exceed the thickness of layer and does not influence on the value of microhardness.

Thus, the use of magnetron sputtering allows to receive a silicon cover on a nitinol substrate, where the obtaining thickness is enough for creation the porous structure. It is identified that the time of treatment has more influence on cover thickness than the power of magnetron.

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TECHNOLOGY OF HARDENING AND IMPROVING THE PERFORMANCE OF HIGH-SPEED STEELS BY GLOW DISCHARGE PLASMA

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The modification of high-speed steels is in interest due to their greatest applicability in the market for the production of cutting tools. They are used for the production of all types of cutting tools in the processing of carbon alloyed structural steels, preferably for the manufacture of thread-cutting tools as well as tools operating with shock loads. Tools made of high-speed steels have relatively low heat resistance, medium hardness, maximum bending strength and toughness as well as high endurance. Improving the performance of high-speed steels is an important task, the solution of which will provide cost-saving materials, energy and labor. At present various processing methods are used to improve performance among which there is plasma treatment.

In the framework of this study samples of high-speed steel were subjected to plasma treatment, the essence of which is that the products are placed in a vacuum chamber on the cathode [1]. Air is pumped out of the chamber and the high voltage power supply circuit is switched on, due to which a potential difference is created between the electrodes, the value of which is set within 0.2-3 kV. As a result, there is a breakdown of the discharge gap with the appearance of a glow discharge. Controlling the high voltage source and vacuum valves, the pressure of the residual gases, the discharge voltage and the current density within the required limits are set. After the processing time of the products in the glow discharge plasma the high voltage is turned off, air is introduced into the chamber and the processed samples are removed. The temperature in the chamber during the plasma treatment is controlled and does not exceed 343 K.

Electro-microscopic, X-ray structural and durometric methods for analyzing the phase composition, structure, and properties of the surface layer were used in the studies. The measurement of the hardness of the working surface of the samples was carried out according to the Vickers method. The study of the effect of treatment in a glow discharge on wear resistance was carried out on an upgraded equipment for testing materials for friction and wear [2].

As a result of this study it was found that the treatment of high-speed steel in a glow discharge leads to grinding and redistribution of the carbide phase in the surface layer to a depth of 20 μm, reducing the dislocation density both in the carbide phase and in the matrix material. Processing samples of high-speed steel leads to an increase in the wear resistance coefficient up to 3 times. After plasma treatment, the hardness of high-speed steel increases to 20% [3, 4].

The results can be used in industrial enterprises and in scientific organizations specializing in the field of plasma processing and materials science, as well as used in the educational process in the development of special courses designed for students of physical and engineering specialties.

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HIGH-RATE DEPOSITION OF CHROMIUM COATINGS BY MAGNETRON SPUTTERING

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Magnetron sputtering of a heated ("hot") chromium target can significantly improve the productivity of Cr coating deposition [1-5]. This is possible due to the formation of additional particle flux by sublimation process on the target surface. Apart from the increase of the deposition rate, a powerful energy flux onto the substrate appears due to the thermal radiation of the sputtered "hot" Cr target. Therefore, in such conditions, we should expect a significant change in the fluxes of matter and energy on the substrate and their specific characteristics (energy per one deposited atom).

This article presents data on the deposition rates of chromium coatings when a "hot" Cr target is sputtered and the energy characteristics of this process. These parameters is necessary to predict the properties of chromium coatings and to choice of the optimal deposition mode of a chromium coating both from the higher productivity and to ensure better functional properties.

The paper considers the influence of substrate pre-heating, discharge power, substrate bias, substrate location relative to the magnetron sputtering system and deposition time on the deposition rates and properties pf chromium coatings.

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EFFECT OF UV IRRADIATION OR DIFFUSE PLASMA ON SURFACE PROPERTIES OF MICRO-ARC CALCIUM PHOSPHATE COATINGS*

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Nowadays functionalization and modification of medical implants are widely used to add new set of properties. Calcium phosphate (CaP) coatings are widely applied as a component of dental, orthopedic and osteosynthesis implants in clinical settings due to porous structure and osseointegration ability [1]. Posttreatment of the CaP coatings using ultraviolet (UV) irradiation or plasma of runaway electron preionized diffuse discharge (REP DD) can improves the hydrophilic properties and variates the surface electrical charge, which significantly affect to the protein and biomolecule adsorption, and cell adhesion [1,2]. However, the changes in activation mechanism, bioactivity stability and cell response of the UV and REP DD treatments of CaP coatings are still not clear. The work was focused on to study the influence of UV irradiation or REP DD posttreatment on the surface properties of the micro-arc CaP biocoatings.

The coating were deposited on commercial pure titanium by the MAO method in anodic potentiostatic mode under following parameters: the pulse duration of 100 μs, the frequency of 50 Hz, the process time of 10 min, and the pulsed voltage of 200 V [1]. The electrolyte contained the phosphoric acid, calcium carbonate and stoichiometric hydroxyapatite. To modify the surface properties of the coatings the different posttreatments by UV irradiation and REP DD in the ambient air were carried out. There were three groups of the CaP coatings: 1) non-treated CaP coating; 2) post treated by UV CaP coating (KrCl-excilamp, $\lambda = 222$ nm, exposure dose of 5.5 J/cm^2, treatment duration varied from 1 to 20 minutes [2]); 3) post treated by REP DD CaP coating (the pulsed voltage of 18 kV with negative polarity, pulse duration of 4 ns, number of pulses varied from 10000 to 80000 [3]).

Wettability studies of not-treated CaP coating showed that the contact angles with water (polar liquid) and glycerol (non-polar) did not exceed 16° and 30°, respectively. Both UV irradiation and REP DD posttreatments of CaP coating leads to decrease of contact angels in 1.5-2 times with both liquids. The free surface energy, which calculated by the Owens-Wendt method [1], of non-treated CaP coatings as well as post-treated by UV or REP DD the CaP coatings was not differed and had high value of ~ 73 mJ/m^2. It is well known, that the free surface energy consists of two components of dispersive and polar ones. In the case of non-treated and post-treated CaP coatings, the polar component is more in ~ 3 times than dispersive component. It indicates the presence of strong polar covalent bonds in the coatings, such as OH-groups, phosphates, and oxides. After UV or REP DD post-treatment the redistribution of the values of the polar and dispersive components of the free surface energy of the CaP coatings was observed.

Infrared spectroscopy showed that the intensity of adsorption bands of the OH- and PO_4- groups increased in the coatings after UV post-treatment and decreased in the coatings after REP DD post-treatment in compared with non-treated CaP coatings. These results can indicate the possibility of redistribution of the electrical charge on the surface depending on the type and condition of the post-treatments.

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CONTACTLESS PARTICLE FILTERING BY ALTERNATING ELECTRIC FIELD

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The problem of gas filtering during the environmental degradation is very important problem in nuclear power engineering, mechanical engineering, the chemical industry and other industries. The electrodynamic traps (Paul traps) can be used in contactless filtration processes, monitoring and diagnostics of microparticles and aerosols in gases.

In the work the theoretical and experimental results on charged particle filtering are shown. Particles were previously charged in corona discharge unit and then captured inside quadrupole electrodynamic trap. The areas of particle confinement as the dependencies on geometries of the trap, the parameters of alternating voltage, gas flow velocities and particle parameters (charge, size, density) were found. The results showed the possibility of selective particle filtering.

Also particle capturing inside electrodynamic trap can be used for particle's parameters diagnostics and particle separation.

HYBRID METHODS FOR OBTAINING PLASMA CHEMICAL COATINGS

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The formation of thin-layer vacuum coatings with various operational parameters allows to significantly increase the range of application of modified materials. To intensify the modifying action of thin-layer coatings, various methods of substrate activation are used [1]. For example, in [2], the influence of the pulsed high frequency voltage applied to the substrate on the crystallite size during the deposition of a TiN coating was considered. It was established that during pulsed deposition of coatings, there is a significant decrease in crystallite sizes from 60 nm to 10 ÷ 15 nm. The nature of this structural behavior is associated with the formation of a highly dispersed non-equilibrium grain structure with a high dislocation density. Methods are proposed for treating a solid dielectric substrate with high-frequency plasma, which leads to a decisive influence on the deposition process of metal films of the electret structure formed due to the redistribution of induced and adsorbed charged particles in the surface layers of the dielectric substrate. As a result of the application of this method of processing the substrate, coatings with enhanced adhesive strength and microhardness are formed. The aim of this work is to develop hybrid methods for hardening metal-working tools, which consist in combining methods of plasma-chemical deposition and cryogenic processing. Tribotechnical studies were carried out on a FT-2 type friction machine, which operates according to a reciprocating scheme, the stroke length of the indenter from 5 to 50 mm under dry friction conditions (counterbody), made of steel and ground on a flat flat surface with emery cloth or grinding paste to arithmetic average deviation of the surface profile Ra = 0.1 - 0.3 microns. The samples were fixed in the friction machine clamp, rubbed with a “coarse calico” cloth, bleached, dipped in ethanol, the working sphere and the working surface of the steel disk (counterbody), and then dried for two minutes at room temperature. The tests were carried out with a normal load on the sample up to 20 N, a linear sliding speed of 0.036 m / s, and a surface temperature of steel (20 ± 5) ºC. During the conducted research it was established that during cryogenic treatment of zirconium carbonitride coatings with short exposure intervals (120-360 minutes) in cryogenic liquid, the strength characteristics of the coatings increase, a further increase in the exposure time (24-48 hours) does not lead to a further increase in the strength characteristics. The increase in strength characteristics may be explained by the formation of a fine-grained structure in the coating layer, as well as the formation of a nano-dispersed phase. The tribological characteristics of composite coatings based on zirconium carbonitride, subjected to cryogenic treatment, are investigated. An increase in the wear resistance of the coatings during cryogenic treatment has been established. With increasing shutter speed in a cryogenic environment, wear resistance increases and friction coefficient values decrease. Cryogenic treatment of coatings of complex chemical composition obtained by vacuum technologies in the medium of the reaction gas during deposition on steel substrates leads to ambiguous results. According to acoustic emission data, the treatment of ZrCN compounds formed on high-speed steel in liquid nitrogen leads to a decrease in the adhesive interaction with the substrate. This effect is manifested to a greater degree at longer exposure times of the coating in a cryogenic liquid. Heat treatment of ZrN coatings formed on steel R6M5, with small time intervals of exposure to cryogenic liquids, can increase the adhesive interaction in the “substrate-substrate” system.

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MODIFICATION OF DIE STEELS SURFACE IN A PLASMA OF NON-SELF-SUSTAINED GLOW DISCHARGE [*]

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Thanks to a combination of high mechanical characteristics and good technological effectiveness at a relatively low cost among structural and tool materials the most widespread at present and perspective for application in the future will be steel. Therefore, the improvement of existing and the creation of new methods of treatment of steels is an actual scientific and technical task. The vacuum ion-plasma surface modification methods, in particular, nitriding, are considered as the most progressive to improve the service properties of details. The nitriding in the plasma of low-pressure discharges (~ 1 Pa) allows to control independently main operating parameters (ion current density on the material surface, ion energy, product temperature). A non-self-sustained glow discharge with a hollow cathode is promising for plasma generation in large (~ 1 m^3) vacuum volumes [1]. The purpose of this work is to define the influence of nitriding process parameters (ion current density, electrical bias voltage) on the regularities of structure and phase composition formation in the surface layer of Cr12MoV and Cr6WV die steels. Studies of the influence of the structure and phase composition of the surface layer on the physico-mechanical characteristics (wear resistance, microhardness) of steels were carried out. The results of scientific work are of considerable interest for the further development of technological modes of exhaust die tools surface treatment.

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COMPLEX MODIFICATION OF THE SURFACE OF HIGH-SPEED STEEL IN LOW-TEMPERATURE HIGH-DENSITY PLASMA *

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Today, the aircraft engine industry is actively increasing the requirements for structural materials in order to improve the basic characteristics of the engine: increased thrust, increased efficiency, reduced fuel consumption. In this connection, the working temperature in gas turbine engines increases and hard-to-use heat-resistant alloys are increasingly used. The low machinability of these alloys is determined by their physicomechanical properties [1,2]. Given this trend, the requirements for metal-cutting tools are also increasing (cutters, cutters, slotting tools, etc.).

To solve the problem of increasing the durability of metal-cutting tools used in the aviation industry from high-speed steels and hard alloys, a method for complex surface modification in low-temperature high-density plasma has been proposed, including ion nitriding and subsequent formation of multi-layer nanostructured coatings based on intermetallic compounds of the Ti-Al system synthesized in reactive gases O, C, N environments. Studies of the effect of low-temperature nitriding and subsequent formation multilayer coatings based intermetallic Ti-Al system to change the microhardness of the surface layer and the wear resistance of tool materials.

A technological process has been developed for complex modification of the surface of tool materials in low-pressure discharges, including low-temperature nitriding and subsequent deposition of multilayer coatings based on intermetallic compounds of the Ti-Al system. The results of production tests of metal-cutting tools processed by the developed complex technology are presented.

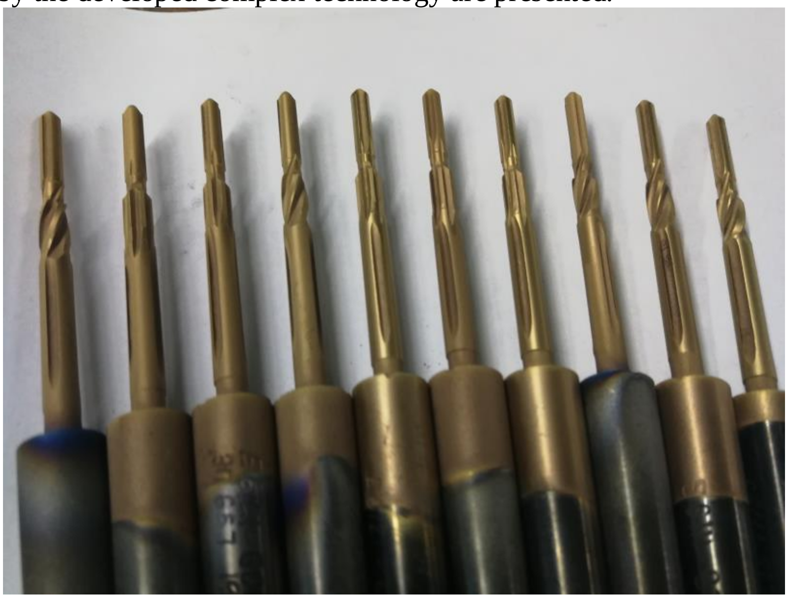

Fig. Metall cutting tools after complex modification of the surface of high-speed steel in low-temperature high-density plasma

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INFLUENCE OF ULTRASONIC WAVES DURING MICRO-ARC OXIDATION ON STRUCTURE AND PROPERTIES OF CALCIUM PHOSPHATE COATINGS *

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The aim of the present work was to study the effect of external uninterrupted ultrasonic (US) or pulsed ultrasonic (PUS) waves during the micro-arc oxidation (MAO) on the growth rate, structure and properties of calcium phosphate (CaP) coatings formed on the commercial pure titanium (Ti) surface.

Synthesis of the CaP coatings on Ti samples was carried out by the MAO method using the Microarc–3.0 installation in the electrolyte and under the conditions described previously [1]. There were three types of the coatings depending on the conditions of external US: 1) MAO-coating (without US); 2) MAO/US-coating (with US, P = 100 W, υ = 35 kHz); 3) MAO/PUS-coating (with PUS, P = 35 W, υ = 37 kHz).

It is seen in Figure 1a, during the MAO process the current density decreases monotonously due to the formation and thickness growth of the dielectric CaP coating. It should be noted that the MAO process under the action of US of PUS is characterized by a higher current density than that without additional US. Figure 1b, c confirms this by the fact that the increase in the coating thickness and surface roughness (Ra) occurs more intensively with additional US than without it.

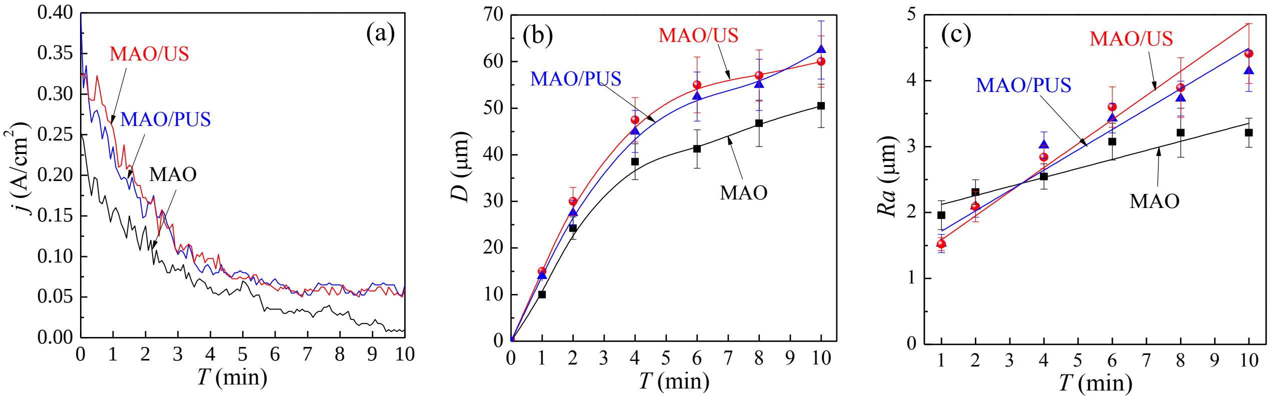

Fig. 1. Graphs of the MAO current density (a), the coating thickness (b) and roughness (c) against the MAO time for different types of the coatings

SEM studies showed that the applied external US field during the MAO process effects on the structural and morphological properties of the coatings. The surface morphology of the coatings formed without UV is represented by the structural elements of spheroidal shape (sphere) with open pores. However, under the action of external US there are destruction of structural elements and filling pore spaces with fragments, which leads to a decrease in surface porosity from 25 to 12 %. At the same time, the internal porosity of the coatings increased from 25 to 40 % due to the formation of macro-pores of 15-40 μm in sizes.

It was found that the external US increases the content of Ca and P in the coatings, and there is a structural-phase transition from the X-ray amorphous state to the amorphous-crystalline state with the content of CaHPO4 and β-Ca2P2O7 phases.

Thus, it was shown that high frequencies of ultrasonic vibrations at low amplitude create an acoustic field with a high level of energy, which allows intensifying the processes of mass transfer in the electrolyte, increasing the growth rate of the coatings, as well as controlling the composition, structure and porosity of the formed coatings.

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NANOSCALE DYNAMIC EFFECTS INSTEAD OF TEMPERATURE. LOW-TEMPERATURE STRUCTURAL STATES FORMED BY ION IRRADIATION*

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With decreasing temperature, interatomic distances decrease, the role of covalent bonds increases. This determines the predisposition of binary and multicomponent media to the formation of low-temperature phases, including those with reduced symmetry. From the condition of the minimum of the free energy $F = E - T \cdot S$, it follows that at 0 K, only pure components and stoichiometric compounds or their mixtures are thermodynamically stable. At the same time, at temperatures $T < (0.2 \div 0.3)T_{melt}$, diffusion processes in condensed media are actually frozen and the equilibrium states are unattainable for actually imaginable time intervals.

At present, the important role of nanoscale dynamic effects in the action of ionizing radiation on condensed matter is being actively studied (see review [1]). These effects, which take place during irradiation with accelerated ions (as well as reactor neutrons, fission fragments), remain outside the field of vision of classical radiation physics. They are associated with the processes of explosive energy release in areas of dense atomic displacement cascades with the formation of nanoscale thermal spikes for trillionths of a second, heated to 3000 ÷ 6000 K and higher with thermal pressures of 5 ÷ 40 GPa, in some cases exceeding the theoretical yield strength of materials. These processes occur in the surface layer < 1 μm thick. However, they lead to the formation of post-cascade powerful elastic and shock waves capable of carrying out liquid flow of condensed media on their front, initiating structural and phase transformations that theoretically propagate in metastable media for unlimited distances. In this case, radiation shaking with post-stage waves plays the role of temperature, increasing the atomic mobility without heating the medium.

To prove the significant, and in some cases, decisive role of shock-wave processes (but not radiation-enhanced diffusion), it is necessary to reduce the exposure time of the ion beam in order to eliminate the role of migration processes. It was shown in [2] that the diffusion path length of vacancies in pure aluminum $l = (D/\tau)^{1/2}$ for 1 s is only 0.4 μm. At the same time, in an ideal lattice, the mileage of interstitial atoms in 1 s can reach several tens and even hundreds of microns and decreases only due to the presence of traps and sinks. However, by limiting the exposure time to $\tau \leq 0.001$ s (using special diaphragms), the role of thermal and radiation-enhanced diffusion (from the surface into the rest of the substance) for objects with a thickness of more than several tens of micrometers can be completely excluded.

In this paper, we used temporal apertures, which set the exposure to 0.001; 0.01 and 0.1 s. It was shown that the formation of a short-range and long-range atomic order in iron alloys from 6.25 at. % Si, 6.25 and 8.25 at. % Mn occurs during their low-temperature irradiation ($T < 300$ °C) with low doses of Ar^+ and Xe^+ ions, which is not related to diffusion processes, but is caused exclusively by post-cascade dynamic (shock-wave) effects. The values of the parameters of the short- and long-range atomic order were determined as a result of processing the Mössbauer spectra of samples ~ 30 μm thick (initially disordered by cold plastic deformation) after exposure to accelerated ions. In samples subjected to similar thermal effects, but in the absence of irradiation, atomic ordering processes are not detected.

Thus, as a result of the study, the possibility of accelerated formation of short- and long-range atomic order in the $Fe_{1-X}Y_X$ alloys (Y = Si and Mn), including at temperatures below the thermal threshold for defrosting diffusion, was proved. At that, the increase in atomic mobility is not due to an increase in temperature and acceleration of diffusion, but dynamic post-cascade effects.

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FORMED NANO-W - WC COATINGS ON THE HIGH-SPEED STEEL SUBSTRATE BY THE ELECRODISCHARGE EXPLOSION*

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Electric exploding of a tungsten carbide – cobalt material near-by high-speed steel (HSS) surface forms on it a hardening coating. These coatings raise the cutting tool resistance in 1,5 – 3 times. The essential structure properties of the formed coatings are determined by parameters of contact exploding electrode at the pulse current amplitude from above 1 MA/cm^2 and duration less than 10^{-4} s [1]. The investigations of coating structures were done by optical (Fig. 1) and electronic metallography. They have shown that the contact electric exploding caused the transfer of tungsten carbide and cobalt on the surface of high-speed steel.

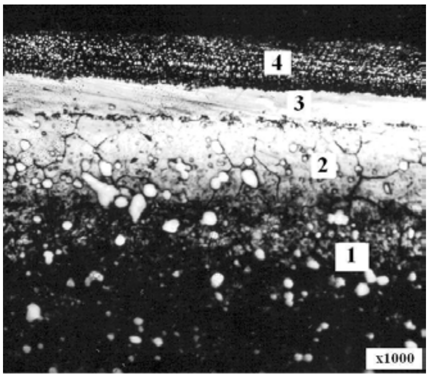

Fig. 1. Optical microscopic image of the polished surface of the WC/W coating on HSS substrate:

1 – unmodified HSS, 2 – modified HSS, 3 – WC layer, 4 – nanostructure (mean grain size < 400 nm) pure W

The breakdown of tungsten carbide – cobalt material took place during electrical exploding. The hardening layers of tungsten carbide and pure nanocrystalline tungsten have been formed upon the surface of high-speed steel as a result of electric exploding. Crystalline grains of tungsten have an almost spherical form and their characteristic size less than 400 nanometers. The layer of tungsten carbide has a high hardness (HV ~ 1800). Localization of heating and subsequent high-speed cooling in the small volume of high-speed steel results in formation of different structures. A metallographic analysis gives the clear picture of distributing of these structures and possibility of direct determination of their thickness. Micro hardness of the coating layers and high-speed steel structures was measured.

Theoretical analysis [2] made it possible to establish the dependence of the volume (ΔV) of an electrically exploded material on the amplitude of the electric current pulse - J and the properties of the material (electrical resistivity - ρ and boiling point – T_b):

$$\Delta V \sim \rho \cdot J^2 / T_b^4 , \tag{1}$$

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THE TRANSMISSION SPECTRUM SWITCHING SPEED OF ELECTROMAGNETIC BAND GAP PLASMA STRUCTURE

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During the last decade, there has been an increasing interest in high-speed tunable microwave devices based on EBG structures for use in telecommunication systems that are capable of operating at high power levels. Gas discharge plasma as a control element of such devices has high potential for this purpose due to its variability in electron density and geometry [1]. The properties of one-dimensional EBG plasma structure in the X-band waveguide formed by discharges at low pressure were described in [2]. In [3], the possibilities of microwave control by long pulse atmospheric pressure discharges were demonstrated. The switching speed of transmission of such EBG plasma structure is under investigation in this work.

The one-dimensional plasma EBG structure is formed by three pulse discharges at atmospheric pressure in a waveguide with rectangular cross-section 23×10 mm^2. Discharges are ignited between two electrodes (1 mm in diameter, interelectrode gap is 11 mm) in quartz tubes with an inner diameter of 1.6 mm and placed perpendicular to the wide walls of waveguide with period of 30 mm. Helium, argon and Ar-O_2(<2%)-H_2(2%) mixture at flow rates about 1 liter/min are used as working gases. The mixture is needed for the diagnostics purposes. The ignition of the discharges is realized from one high voltage square pulse (Nanogen 1 from RLC electronic) of variable amplitude up to 5.5 kV and duration of 1 μs (pulse rise time is about 25 ns).

The experiments are performed at different pulse voltages from breakdown voltages depending on working gas (Fig. 1a, vertical dashed lines) up to 5.5 kV. In Fig. 1*b*, the waveforms of current pulse (1) and corresponding microwave signal (2) passed through EBG structure are shown. The dependence of current growth rate and fall rate of transmitted microwave power on the applied voltage pulses were determined (Fig. 1a). The switching time is less in Ar and Ar-O_2-H_2 discharges (about 35 ns) than in case of He (150 ns) discharges, while the decay time of afterglow plasma is shorter in case of mixture (about 4 μs).

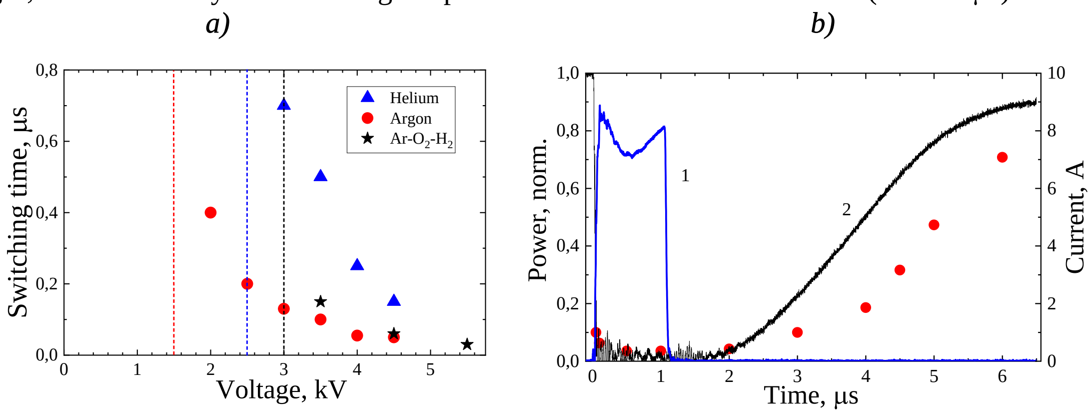

Fig. 1. a) The switching time vs pulse voltage for different gases. Dash lines are breakdown voltages; b) The waveforms of current pulse (1) and microwave signal passed through EBG structure (2) in case of mixture and simulated transmission (circles)

The time resolved H_α and H_β line profiles for Ar-O_2-H_2 mixture at current about 8 A were registered using ICCD camera with spectrometer (PIMAX and ACTON SP300i from Princeton Instruments). Time evolution of electron concentration was determined. The discharge diameter estimated from a series of photos made with ICCD camera is about 0.25 mm. Modeling of EBG plasma structure transmission is performed using the Ansoft HFSS software. The simulation results of transmission (Fig. 1*b*, symbols) are in satisfactory agreement with experimentally registered ones.

The obtained results demonstrate the possibility of developing high-speed microwave elements (switches, limiters, attenuators) under plasma control operating at high-power microwaves.

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INFLUENCE OF GAS DISCHARGE PLASMA ON FILMS OF COMPLEX COMPOSITION FORMING PROCESS AND PROPERTIES*

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Currently, to obtain films of complex composition, ion-plasma methods are of great interest, which allow varying the technological parameters to produce films of various modifications and different compositions for various applications.

The main disadvantage of these methods is the negative impact of electron-ion bombardment of the growing film, which can lead to the breakdown of dielectric films, the formation of a mobile charge, an increase in fixed charge and the density of surface states [1]. At the same time, the degree of impact of electron-ion bombardment depends on the films producing methods implementation.

The authors have developed ion-plasma sputtering methods based on the Penning discharge and magnetron sputtering system, which were used to develop technologies for producing insulating and conducting films of complex composition, representing various compounds of oxides and nitrides of Al, Si and In metals [2]. In particular, this paper discusses the results of studying the mechanism of the formation of the stoichiometric compounds of thin films of complex composition, formed by the method of ion-plasma sputtering in the medium of active gases. The kinetics of their growth is investigated, the results of studies of changes in the properties of thin films and substrates during ion-plasma processes, as well as the study of changes in the characteristics of the elements of microelectronics formed on their basis during their electron-ion bombardment are presented.

It was found that during ion-plasma sputtering of metal targets in the medium of active gases, the formation of final compounds (Si_3N_4, AlN, Al_2O_3 In_2O_3:Sn) occurs on the substrate, when atoms and metal ions arrive, as well as gas molecules and ions of the working atmosphere.

It was established that in the process of deposition of thin films of complex compounds by ion-plasma methods, even at low discharge power, the substrate temperature significantly increases. At the same time, directly heating the substrate to form stoichiometric films of complex composition plays the most important role, contributing to the formation of the crystalline phase [3]. However, the plasma effect is manifested not only in the heating of the substrate surface, but also in the appearance of a negative potential on it.

The effect of electron-ion bombardment was studied in *MDM* and *MDS* capacitors. Si_3N_4 films served as dielectric capacitors. Different degrees of plasma effect on the film properties were provided by changing the substrate distance to the discharge. The parameters of the *MDM* capacitors remained fairly good with the intensity of electron-ion bombardment that takes place in the Penning gas-discharge chamber in the case of an isolated substrate under a floating potential. Electron-ion bombardment has a more significant effect on the characteristics of *MDS* capacitors. We investigated the effect of electron bombardment on the properties of the silicon-nitride silicon interface. For this purpose, capacitance-voltage (*C–V*) characteristics were obtained for the case of a floating potential on the substrate and the substrate that was at the anode potential. The *C–V* characteristics showed that an increase in the intensity of electron bombardment leads to the appearance of a large positive charge at the interface and to an increase in the density of surface states N_T. Vacuum annealing significantly reduces N_T, but the positive charge does not decrease.

Thus, the formation of films by ion-plasma methods is accompanied on the one hand by negative impact of electron-ion bombardment on a substrate with a growing film, and on the other hand, low-energy electron-ion bombardment can contribute to the formation of films of stoichiometric composition.

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LOW TEMPERATURE ICP ETCHING InP/InGaAsP HETEROSTRUCTURE IN Cl_2-BASED PLASMA*

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At the present time, InP is one of the base materials of integrated optoelectronics. The development of optoelectronic devices often requires the formation of waveguide structures with a high aspect ratio and a smooth surface morphology. For the formation of such structures is widely spread method of ICP etching in Cl_2 based plasma. The advantage of this method is the possibility of independent control of the density and energy of plasma ions, which provides flexible control of the etching conditions. However, chlorine-based processes have a significant disadvantage. In the process, the $InCl_3$ compound with low volatility at room temperature occurs in etching products, which leads to the formation of grass-like defects on the surface of etched structures. Usually, to solve this problem, the substrate is heated to 150-200 °C and above [1, 2]. It prevents redeposition $InCl_3$ on the surface of the etched structure and the formation of grass-like defects. Another way to remove $InCl_3$ from the surface is to enhance the role of the physical component of the etching process [3].

This paper presents the optimization of the low-temperature ICP etching process of an InP/InGaAsP heterostructure in a $Cl_2/Ar/N_2$ plasma. The relationship between RF power and process pressure on the etching profile of the heterostructure and the formation of grass-like defects is shown. The possibility of using multi-stage etching processes to reduce the surface roughness of the etched heterostructure is considered. The developed etching process has a high anisotropy. The angle of inclination of the etching profile is close to 90º. Surface roughness does not exceed 30 nm. Also, it has low selectivity with respect to the InP and InGaAsP layers. Fig. 1 shows a SEM image of the cross section of the etched InP/InGaAsP heterostructure after etching in optimized etching conditions.

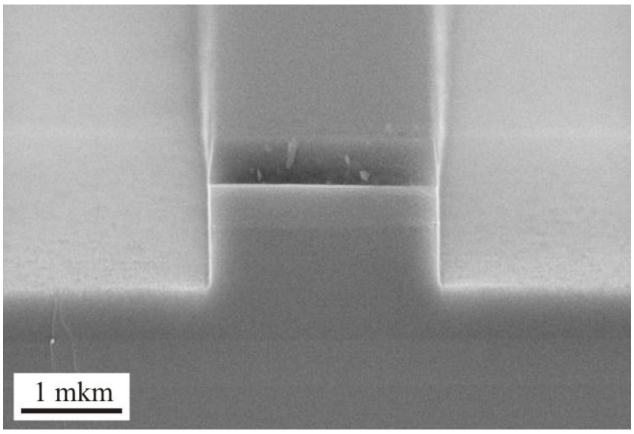

Fig. 1. SEM image of the cross section of an InP/InGaAsP heterostrucrute after ICP etching in a $Cl_2/Ar/N_2$ plasma.

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INVESTIGATION OF CATALYST OBTAINED FROM ALUMINUM OXIDE PRODUCED BY PLASMA SYNTHESIS[1]

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Nano-sized aluminum oxide is used in many industries, including widely used as a substrate for catalysts. As is known, the formation of an active and stable catalyst is influenced by the morphology, phase composition and chemical nature of the carrier and the active phase. The chemical nature of the aluminum oxide surface, which means the state and structure of the hydrate cover, the concentration and the distribution of acid-base centers by strength, determines, on the one hand, the adsorption and catalytic properties of the oxide, and on the other hand, allows controlling the reactivity of the surface in solid-phase reactions. These characteristics are largely determined by the degree of surface hydration and depend on the nature and texture of the starting materials, the method of preparation and the crystallographic structure of aluminum oxide.

A sample of aluminum oxide was obtained by the method of plasma thermal decomposition of aluminum nitrate [1]. The plasma torch is powered from an AC power source (50 Hz) with a voltage of 6 kV [2]. This voltage allows to reignite the electric arc without current skips. To stabilize the electric arc in the gap between the electrodes, plasma gas (air) supply is organized. One of the sides of the plasma torch is plugged, and through the second side the stream of air plasma (1 g/s) is fed to the reaction volume. To determine the acid-base properties, the produced aluminum oxide was sequentially impregnated with cerium nitrate and nickel nitrate. The synthesized product was controlled by XRD. The nature of the effect of nickel oxide on the aluminum oxide carrier was studied using the following physicochemical methods: X-ray phase analysis (XRD), scanning electron microscopy (SEM) and IR spectroscopy. The functions of the Hammett and the specific surface area of the samples were also determined.

The pH-metry method was used to determine the predominant type of acid-base centers of the surface: the acid and Lewis base. The Hammett function was evaluated using the pH-metry method, which is based on the kinetic control of the pH of an aqueous solution in contact with the solid. Measurement of the pH made it possible to establish the type of acid-base centers on the surface of the samples: before the impregnation with nickel oxide, the acid sites predominate on the aluminum oxide surface, and after the impregnation the main acid sites predominate.

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ELECTRIC DISCHARGE DESTRUCTION OF REINFORCED CONCRETE SLEEPERS WITH DIFFERENT MODES OF PULSE POLARITY

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Analysis of publications in the world on the topic of electrical discharge destruction shows that today interest in electrical discharge technologies for processing materials, such as drilling or crushing, is rapidly increasing [1-6]. However, publications associated with the destruction of concrete products and removal of the surface layer is not enough.

Experimental data of the destruction of reinforced concrete sleeper in the system of electrodes placed on the sample were obtained. The tests were carried out at different modes: bipolar pulse, pulses with positive and negative polarities. The optimal charging voltage was determined, which was chosen according to the criteria for the occurrence of breakdown at the top or in the decay of a pulse signal without overvoltages in the system with the given interelectrode distance.

During the experiment, the sample was destroyed before the first layer of reinforcement (Fig. 1.), and it can be noted that the destruction near the reinforcement shows the worst result among all the stages of destruction, since the amount of consumed specific energy is more than in all other stages. Also, there is the smallest result in terms of the volume of the broken-off material. This happens due to the fact that a significant part of the impulses falls on the reinforcement, and not on the destruction of concrete.

As a result of destruction, the reinforcement can be completely removed without any additional effort.

Fig. 1. View of the sample with the installed electrode plate system.

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ADVANCED FUNCTIONAL COATINGS DEPOSITED USING SUPERSONIC ATMOSPHERIC PLASMA SPRAYING*

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The development of thermal spraying (TS) methods over the past decade has been associated with an increase in the velocities of the sprayed particles in order to improve coating characteristics such as density, hardness, adhesive strength, corrosion resistance, etc. The guidelines in this area are high velocity oxygen fuel (HVOF) and detonation spraying (DS) methods, in which gas flows at a speed of 2000…2500 m/s provide acceleration of particles of the material up to 500…800 m/s and above. However, advances in the development of supersonic atmospheric plasma spraying (S-APS) equipment in recent years have demonstrated that this method is capable of providing comparable parameters for particles of the dispersed phase and the quality of coatings. In addition, in recent years, plasma spraying of suspensions and liquid precursors (SPS and LPPS) has developed intensively, in which the formation of coatings of small particles (0.1–3 μm) requires an increase in their velocity above 500 m/s.

This paper presents the latest results of the ITAM team's work in the development of the supersonic version of a spraying DC plasmatorch PNK-50. Increasing the speed of the plasma flow to the level of 2000 ... 2500 m/s allows the application of functional coatings with outstanding characteristics. Thus, using the low-enthalpy (low-temperature) S-APS regime, high-density wear-resistant coatings from powder materials of NiCrSiBC metal alloy and WC/CoCr composite material were obtained, demonstrating characteristics previously available only to high-speed HVOF and DS methods. The use of the high-enthalpy (high-temperature) regime of supersonic plasma equipment in the methods of SPS and LPPS made it possible to obtain advanced coatings of ZrO_2 ceramics. Thermal barrier coatings (TBC) with a columnar structure, high-density YSZ coatings for the formation of solid oxide fuel cells (SOFC) electrolytes, as well as coatings with a pronounced bimodal surface profile with super-hydrophobic effect were obtained.

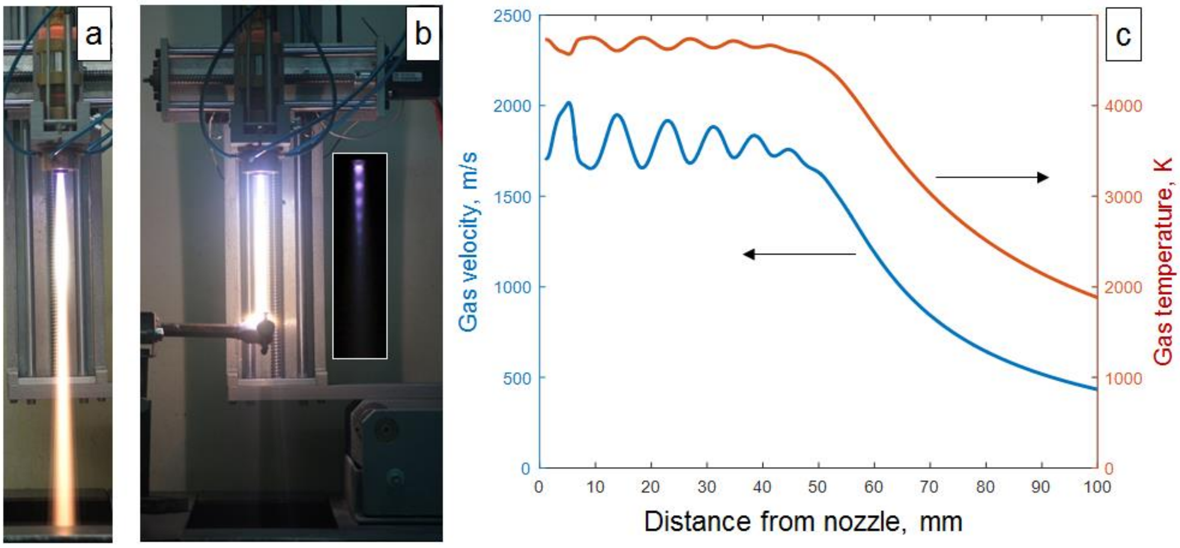

Fig. 1. Supersonic plasma spraying using PNK-50 torch: a) high-velocity spraying jet; b) deposition process of WC/10Co4Cr coating; «shock diamond» are shown in the insert; c) calculated gas temperature and velocity distribution on the axis of the jet in high-enthalpy supersonic plasma flow.

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THE SIGNAL RADIATION BY THE PLASMA ASYMMETRICAL DIPOLE ANTENNA

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A plasma asymmetric dipole antenna (PADA) is an analogue of a metal asymmetric dipole antenna (MADA) with a round screen, and consists of a pin (dipole arm) connected to the central conductor of a coaxial cable and a conductive disk connected to an external conductor of a coaxial cable. In the case of a plasma antenna, the metal pin is replaced with a gas discharge tube with a plasma. Such type of plasma antenna from discharge tube is most popular [1]. Plasma in a tube can be generated either by an external source connected to a gas-discharge tube, or by a source of a radiated high-frequency signal (generator or coherent transmitter). Creating a plasma in the discharge tube of the PADA due to the signal energy from a transmitter allows you to simplify the connection pattern of the plasma antenna and make it similar to the MADA connection. The most convenient way to feed the PADA from the transmitter, as in the case of the MADA, is to connect them using a coaxial cable. With this method of connection, the plasma gas discharge tube is connected to the central (inner) conductor of the coaxial cable, and the screen is connected to the external conductor of the coaxial cable.

Despite the large number of the PADA studies [2], in this work, for the first time, we made a comprehensive research on the characteristics of the signal radiated by the PADA. The electromagnetic field patterns, radiation patterns and signal spectra of the plasma and metall antenna were studied by analytical, numerical and experimental methods. Numerical simulation was carried out in the full electrodynamic code KARAT [3] using the FDTD method for calculation of electromagnetic field and the Drude theory and the PIC method as plasma models.

The study consisted of three parts. In the first part, the dispersion relation for the surface electromagnetic wave was numerically solved for the case of an unmagnetized plasma cylinder, the distribution of the electromagnetic field in the near field, and the radiation patterns were calculated in the KARAT code on the Drude model for different plasma densities, the radiation pattern for the PADA and the MADA were experimentally measured. It was shown that there are three modes of operation of a plasma asymmetric dipole antenna, determined by the dispersion characteristic: surface wave modes (nonradiative), nonlinear and linear. These modes are determined by the ratio of the plasma Langmuir frequency and the frequency of the supplied electromagnetic wave and related to the propagation conditions of the surface electromagnetic wave on the plasma cylinder. In the linear mode, the radiation pattern and the field distribution of the plasma antenna are close to those of a metal antenna.

In the second part, the radiation spectra of the unmodulated sinusoidal oscillation with the frequency near 450 MHz were studied using numerical simulations using the PIC plasma model and experimental measurements. As a result, it was found that the amplification of the components in the spectrum of the oscillations at the harmonics of the frequency 450 MHz when it was radiated by the PADA. The amplification of harmonics in the spectrum of the unmodulated oscillation depends on the power of the electromagnetic wave supplied to the antenna and the matching of the antenna with the feeder path.

In the third part, the radiation of a narrow-band frequency-modulated signal by the PADA was experimentally measured. The power of nonlinear combination frequencies in the spectrum of a narrowband frequency-modulated signal radiated by a plasma asymmetric dipole antenna is lower than in the spectrum of the same signal from by a metal asymmetric dipole antenna. In the spectrum of the detected signal received from the plasma antenna, the power at the second harmonic of the frequency of the modulating oscillation is less than for the signal from the metal antenna.

The report is dedicated to the memory of Professor A.A. Rukhadze.

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CHARACTERIZATION OF ALUMINA DEPOSITION PROCESS IN A HIGH POWER PULSED REACTIVE MAGNETRON SPUTTERING*

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Transparent aluminum oxide coatings are extensively used in various applications in electronics, mechanics, optics, etc. They demonstrate outstanding mechanical properties, high resistance to abrasion and corrosion [1, 2], coupled with attractive optical properties for enhancing characteristics of lenses and producing reflection-type polarizers [3].

We studied the deposition process of alumina coatings in a high-current impulse magnetron discharge (HCIMD [4, 5], or long HiPIMS). The aluminum target was sputtered in Ar/O_2 gas mixtures with different partial pressure ratios. Total pressure was 0.5 Pa. The pulse duration was varied in millisecond range, with different duty factors. Both peak and average cycle power were changed in order to determine the most appropriate sputtering conditions. Dependence of alumina mass deposition rate on O_2 gas content for different pulsed discharge time signatures is shown in Fig. 1.

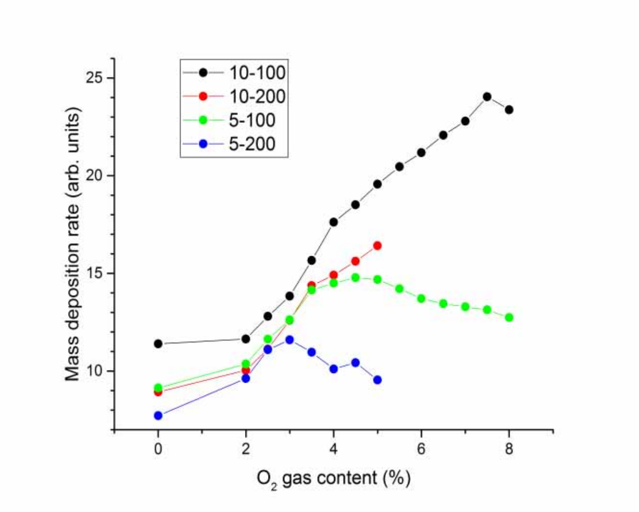

Fig. 1. Mass deposition rate of alumina depending on O_2 gas content

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IRRADIATION OF A WHITEFLY BY SUBMOCROSECOND ELECTRON BEAM AT ATMOSPHERIC PRESSURE*

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A submicrosecond electron beam (up to 250 keV, 500 A, 200 ns) is used at atmospheric pressure for irradiation of a whitefly in this work. The electron beam was ejected from vacuum diode of pulsed electron accelerator directly to atmosphere without of drift chamber. Whitefly probes were irradiated at various distances from exit window of the accelerator. Energy distribution of the electron beam was measured for dose estimation. Lethal and shock effects were demonstrated for whiteflies at various distances and beam pulse number. Single pulse of the electron beam at distance 80 mm from exit window leads to total disinsection of the whitefly probe.

* Preparation of the experiments and analysis of the data were supported by RFBR grant # 18-32-00184mol_a. Electron beam irradiation carried out at Tomsk Polytechnic University within the framework of Tomsk Polytechnic University Competitiveness Enhancement Program grant.

TITANIUM SURFACE TEXTURING INDUCED BY ARGON ION BOMBARDMENT IN AN ICP DISCHARGE

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Currently, plasma technologies are widely used to improve the quality of products manufactured for a vast amount of applications ranging from cutting tools to medical implants. Studies of the properties of micro- and nanostructures on the titanium surface, as well as methods for their preparation, are of great interest, especially for orthopedics and implantology since the microtexture of implants affects the speed and quality of the material integration into the bone tissue.

In this contribution, we studied the effects of the argon ion bombardment parameters on the surface structure of samples obtained during plasma processing in an inductively coupled plasma (ICP). Samples of VT1-0 Russian grade titanium were irradiated at different radiofrequency power P_{rf} = 700, 1200, and 1500 W. The irradiation was carried out in a pulsed fashion with frequency f = 35 kHz. The sample current was varied by changing the duty factor D = 10–80%. The energy and the average ion flux on the sample determined the temperature of the sample T = 500–750°C. Plasma density was measured by a Langmuir probe. The samples were analyzed in a scanning electron microscope (Fig. 1). For each of the surface topography modes obtained, the sputtering yield was calculated.

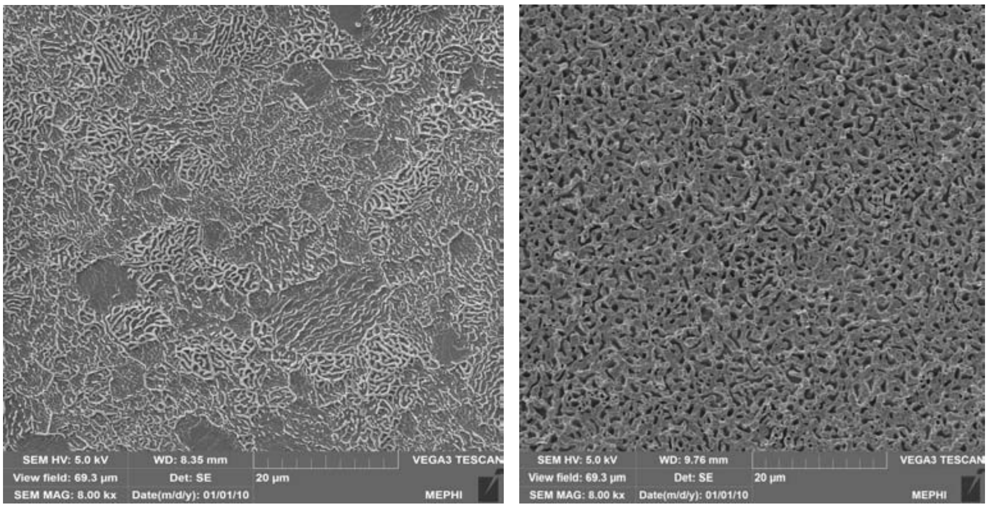

Fig. 1. Different modes of VT1-0 surface microtexture obtained by irradiation in Ar plasma

It is assumed that the development of such structures on the surface is determined by the influence of sputtering, melting, the presence of local crystal lattice defects, changes in grain sizes during heating, temperature gradients on the surface, and phase transition of the crystal lattice.

In the course of the work, the influence of the plasma treatment temperature, the duty factor of the pulsed periodic irradiation, and the plasma density on the nature of the obtained structures was examined. Understanding these dependencies would enable controlling and producing structures with characteristic dimensions required by a certain application.

PULSED CORONA DISCHARGE OXIDATION OF AQUEOUS DISSOLVED ORGANIC SUBSTANCES

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Atmospheric pressure gas-phase pulsed corona discharge (PCD) is a promising instrument in water oxidative treatment. Active oxidant species formed in air or oxygen discharge plasma, such as hydroxyl radicals (OH) and ozone (O_3), react with aqueous organic and inorganic dissolved impurities resulting in their decomposition and, also, water disinfection.

High reactivity of hydroxyl radicals and their short lifetime requires generation of the discharge plasma in close vicinity to target pollutants. Underwater and gliding surface discharges frequently used for this purpose concentrate energy in a few narrow channels resulting in radicals' recombination and low energy efficiency. The highest yield of active species and the treatment energy efficiency is achieved in gas-phase PCD. However, reactive species are largely produced in the gas phase, at a distance from the water surface, making the energy density in PCD with optimized mass transfer conditions in the plasma-water contact equipment the key factor for maximum oxidation efficiency.

The impact of process parameters on the oxidation efficiency of organic substances of various oxidation kinetics was studied. The discharge was formed in a wire-plate electrode system placed into a rectangular stainless-steel reactor sized 0.2×0.2×1.0 m. High-voltage wire electrodes were horizontally positioned between vertical grounded plates having the treated water flow perpendicular to wires. The distance between the wire and plate electrodes comprised 20 mm. Pulsed corona was energized by high-voltage positive polarity pulses with 200-300 ns duration, 20 kV amplitude and 0.3 J pulse energy. Water was dispersed in air flowing through a perforated plate: free-falling water droplets and jets passed through the discharge zone. The volume of treated samples was 20 L. In batch experiments, solutions were prepared in a storage tank, fed to the reactor for treatment, and recirculated after the treatment to the same tank. Solutions of humic acid sodium salt and oxalic acid were used in the experiments as target pollutants with relatively slow oxidation rates. Humic substances are widespread natural contaminants frequently found in natural waters. Slower reacting oxalate is a common byproduct of organic substances oxidation.

Experiments showed that parameters of the electrode system, such as the distance between the neighboring high voltage electrodes (10-30 mm) and the length of the high-voltage wire (8-25 m), did not have a noticeable influence on the oxidation rate of model substances, provided the discharge energy remained constant. With the same pulse energy, decreasing the wire electrode length from 25 to 8 m resulted in the volumetric energy density increased for more than three times. However, the discharge parameters, such as the energy, ozone yield and oxidation rate remained practically unchanged.

Increasing the energy consumption by changing the pulse repetition frequency from 200 to 860 pulses per second resulted in the increased oxidation rate at a reduced oxidation efficiency. The effect was better seen with slowly reacting oxalate, which was more efficiently oxidized at a lower pulse repetition rate, i.e. longer treatment time.

Accelerated water flow resulted in more efficient oxidation of oxalate: the oxidation rate increased by 30-40% when the flow rate changed from 0.5 to 2.4 $m^3 \cdot h^{-1}$, due to the increased water-air contact surface. However, improved contact between treated solutions and ozone present in the PCD reactor by its recirculating by means of a Venturi tube did not bring better oxidation.

An attempt was made to increase the residence time of water in the discharge zone by introducing polyethylene shavings into the inter-electrode area. This resulted in 30% lower oxidation efficiency of humic substances due to increased ohmic losses and discharge concentration visible by the discharge glow at fixed points of the plastic bed leading to high temperature in the discharge channels and lower yield of active species.

The most important parameter influencing the efficiency of organic substances oxidation appeared to be the discharge power, i.e. pulse repetition rate. Further research is needed in the mass transfer impact to oxidation efficiency.

ANTIBACTERIAL POTENTIAL of Zn- and Cu- SUBSTITUTED HYDROXYAPATITE COATINGS DEPOSITED by RF-MAGNETRON SPUTTERING: STRUCTURE and PROPERTIES[1]

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A tremendous number of traumatic cases associated with the bone fractures fostered the market need for implants that can provide immobilization of bone fragments using minimally invasive surgical access and quicker recovery of the patient. In order to address this problem, we introduced newly developed intramedullary implants. Those implants already proved their effectiveness in cases where fixation of a proximal bone fracture of tubular bones is needed. On the other hand, the problem of postoperative infections still the main challenge for modern health care. In case of severe post-implantation infection revision surgery is usually needed as the treatment with antibiotics does not provide the desired outcome. Therefore, our approach to this challenge lies in the surface modification of intramedullary implants by an RF magnetron deposition of antibacterial calcium phosphate (CaP) based coatings with the addition of Zn or Cu. The ions of Zn and Cu are known to have an antibacterial effect and their application is extensively researched in the biomedical engineering field.

We aim to develop novel bioactive and antibacterial coatings with enhanced osseointegration properties consisted of CaP+Zn and CaP+Cu based materials on Ti-6Al-4V and Ti-6Al-7Nb alloys of medical applications. We aim for improvement of the immunocompatibility of the novel implants as well as their antibacterial properties. And finally, we are working towards a translation from model samples to coated implant prototypes for validation of the improved osseointegration, antimicrobial activity, and immunocompatibility in order to demonstrate the proof-of-concept of the developed surfaces.

The targets for sputtering were sintered from hydroxyapatite with the addition of Zn and Cu ions that is substituting Ca in the cation lattice prepared by mechanochemical synthesis. A vacuum installation, with a planar magnetron operated at 13.56 MHz, was utilized for the CaP+Zn and CaP+Cu deposition. The thickness of the deposited films was measured by Calotest. For the coating's characterization methods such as an X-ray diffraction, scanning electron microscopy (SEM) and atomic force microscopy (AFM) were used. For biological assessment of developed coatings in vitro cytotoxicity test with MG-63 and C2C12 cell lines was used. Antimicrobial testing was performed with E.Coli using a disk diffusion assay.

The estimated thickness of the deposited coatings was in the range of ~1.0 µm for both CaP+Zn and CaP+Cu. An SEM revealed that both types of coatings remain dense, homogeneous without any inclusions and discontinuities. According to AFM, the deposited coatings alter the implants' roughness insignificantly and mostly repeats the shape of an original surface. However, it is possible to detect globular-like surface features of the deposited coatings. The coatings revealed to be quasi-amorphous according to an XRD data. This is beneficial for the coatings stability on the implant that is undergoing mechanical stress during implantation. Moreover, amorphous coatings will be dissolved more quickly releasing antibacterial ions and ensuring the antibacterial effect. Deposited coatings showed the absence of toxic effect in vitro and noticeable antibacterial effect.

In our study, we addressed the problem of antibacterial surfaces for implants and specifically for intramedullary fixator developed by us. We were able to functionalize the surface of an implant with bioactive (Ca and P releasing) antibacterial coatings and performed preliminary study in which we discussed its properties and effectiveness in vitro.

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APPLICATION of GLANCING ANGLE DEPOSITION for MANIPULATION of THIN CALCIUM PHOSPHAPTE COATINGS MORPHOLOGY [1]

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Calcium phosphate (CaP) coatings are a widely researched topic which, over the years, resulted in lots of applications in the field of bone regeneration. It is due to the fact that conventional metallic implants become encapsulated by fibrous tissue, which in turn not only prolongs the healing time, but also leads to implant loosening and eventually premature failure of implantation. Not to mention bear Ti corrosion rate in the physiological fluids which might cause metallosis.

The modern approaches to healthcare are aiming to produce implants with biomimetic properties. These properties are crucial to ensure desirable biological response to the newly implanted material, in the manner that the cells, which are adhered to the surface of such scaffolds can function in a way that is similar to physiological conditions. From that point of view, the formation of a coatings that consists of different types of surface gradient structures and with variation in the level of roughness in submicro- and nanoscale could be of significant interest for biomimetic purposes. Thus, a possibility to manipulate nanotopography attracts much attention in the recent years.

Physical vapor deposition (PVD) of thin films, allowing the deposition of porous and/or columnar-like structured coatings, has been available for some years. In turn, the use of an oblique angle geometrical configuration, or as it is also referred as glancing angle deposition (GLAD) method, is frequently exploited for formation of three-dimensional columnar micro- or nanostructured surfaces. It is generally accepted that the mechanistic factor controlling the nanostructural evolution of the films is a ‘‘shadowing effect”, which prevents the deposition of particles in regions situated behind initially formed nuclei (i.e., shadowed regions) [1].

An emerging method for bioactive coating deposition in the field of PVD is radiofrequency (RF) magnetron sputtering method [2]. Magnetron sputtering is widely used in the formation of coatings for various applications. The continuous interest of scientists for this method is due to the possibility of modifying the coating structure and its physicochemical properties by variation of the deposition parameters. There is a significant interest in radiofrequency (RF) magnetron sputtering of bioactive CaP thin films. This method allows deposition of CaP coatings with a high level of adhesion to substrate.

In our work we show the influence of GLAD geometry on the morphology and structure of thin calcium phosphate films deposited by RF magnetron sputtering method. The method allowed us to manipulate the coating roughness on the submicron and nanoscale levels. A significant change in the coating morphology was revealed when the substrate tilt angle was set to 80º. It was shown that an increase in the coating crystallinity for samples deposited at a tilt angle of 80º corresponds to formation of crystallites in the bulk structure of the thin film. Cross section SEM revealed inner structure of deposited coatings and predominant growth towards the particle flux was easily detectable. The GLAD of complex calcium phosphate material can lead to the growth of thin films with significantly changed morphological features and can be utilized to create self-organized nanostructures on various types of surfaces [3].

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THE TECHNOLOGY OF LOW-TEMPERATURE ION NITRIDING OF AUSTENITIC AND MARTENSITIC STEELS WITH ULTRAFINE-GRAINED STRUCTURE

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Presently in the engineering industry there is an increase in interest in structural materials with ultrafine-grained (UFG) structure [1]. These materials have high strength properties [1,2]. Improving the surface hardness of parts from steels with UFG structure, ion nitriding in a glow discharge is often used. Ion nitriding of steels is carried out at high temperatures (550-600°C), which is unacceptable in the case of processing steels with a UFG structure [3,4]. Therefore, the development of low-temperature ion nitriding technology for such materials is an urgent task.

In the present work, austenitic and martensitic steel grades were subjected to low-temperature ion nitriding in a glow discharge at 450°C, 6 h in gas mixture: nitrogen N_2, argon *Ar* and hydrogen H_2 used installation ELU-5M [5]. Before nitriding, steel samples were subjected to high pressure by torsion (HPT) treatment.

In Fig. 1 shows the microhardness distribution of the surface along the radius of samples of steels of austenitic and martensitic classes with a UFG structure after ion nitriding in a glow discharge at temperatures 450, 500 и 550°C.

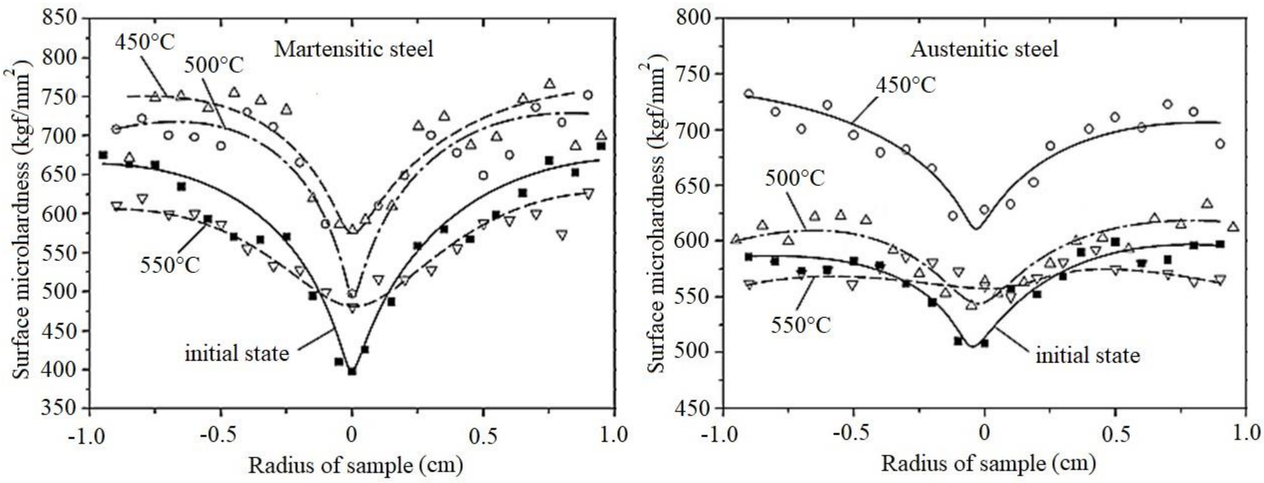

Fig. 1. Surface microhardness distribution by diameter of steel samples after ion nitriding at different temperatures

As a result of the analysis of the obtained distributions (Fig. 1), it was found that in the middle of the radius of the samples, the hardness reaches maximum values for austenitic steel around 580 kgf/mm^2, and for martensitic steel around 650 kgf/mm^2. The maximum degree of hardening (22-25%) was obtained on samples that passed nitriding at a temperature of 450°C (low-temperature ion nitriding). With an increase in the treatment temperature from 500°C to 550°C, the nonhomogeneity of the distribution of microhardness decreases, and the surface hardness decreases due to the onset of recrystallization processes of the UFG steel structure.

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PECULIARITIES OF THE FORMATION OF HIGH-INTENSITY ION BEAMS OF GASES, METALS AND SEMICONDUCTOR MATERIALS*

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The work is devoted to the study of some regularities and features of plasma-immersion formation of high-intensity low-energy ion beams of gases, metals and semiconductor materials. It was shown, that repetitively pulsed gas ion beams are sustainably formed both in the system with spherical and cylindrical focusing geometry at negative bias in the range of 0.6–3 kV, pulse repetition rate from units of pulses per second (p.p.s) up to 10^5 p.p.s, and pulse durations up to 100 μs. The formation of high-intensity metal ion beams requires pre-injection of plasma into the equipotential drift space of the focused beam. The space charge neutralization processes define several features of high-intensity ion beams, including a complex dynamic of focusing and beam instabilities appearing with the increase in beam pulse duration up to 15 μs. The specificity of silicon beam formation is associated with low conductivity of silicon. For the purpose of pulsed vacuum arc plasma generation, the silicon cathodes were neutron transmutation doped on the nuclear reactor of Tomsk Polytechnic University. It was shown, that the process of high-intensity silicon ion beam formation might be accompanied with periodic instabilities of beam transportation and following recovery of space charge neutralization and its transportation. The conditions of sustainable generation of ion beams of gases, metals and semiconductor materials with the current of about 1 A and current densities of 0.5–1 A/cm^2 at accelerating voltages of several kV were defined.

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EFFECT OF THE REACTIVE GAS IMPURITES IN HELIUM PLASMA ON THE FUZZY TUNGSTEN STRUCTURE

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The most pressing issue in designing a fusion reactor is a choice of the first wall material capable of withstanding exposure to hot plasma. At the moment, tungsten has been chosen as the material of the divertor tiles in ITER. Studies of plasma impact on tungsten involves not only interaction with D and T species but also with fusion reaction products (He) and impurity elements of residual gases. The accumulation of helium at high temperatures is accompanied by the growth of nanostructures on the tungsten surface. It is also an urgent task to determine the effect of impurity elements on the surface structure and accumulation of helium.

In work the tungsten samples were irradiated by ions of helium and impurity elements (nitrogen, oxygen) in an inductively coupled plasma (ICP) reactor. Irradiation was carried out at sample temperature of 1200 K, the ion energy of 150 eV, and plasma density of ~ 10^{12} cm^{-3}. The bias voltage was applied to the samples in a rectangular pulsed mode. During He irradiation, N_2, O_2, and their mixtures were introduced in the amount of 1, 2, 4, and 8% of the total pressure. Thermal desorption analysis of He accumulation depending on the presence of impurity elements was carried out. The surface structure was analyzed with a scanning electron microscope. The images of obtained fuzzy structures are shown in figure 1.

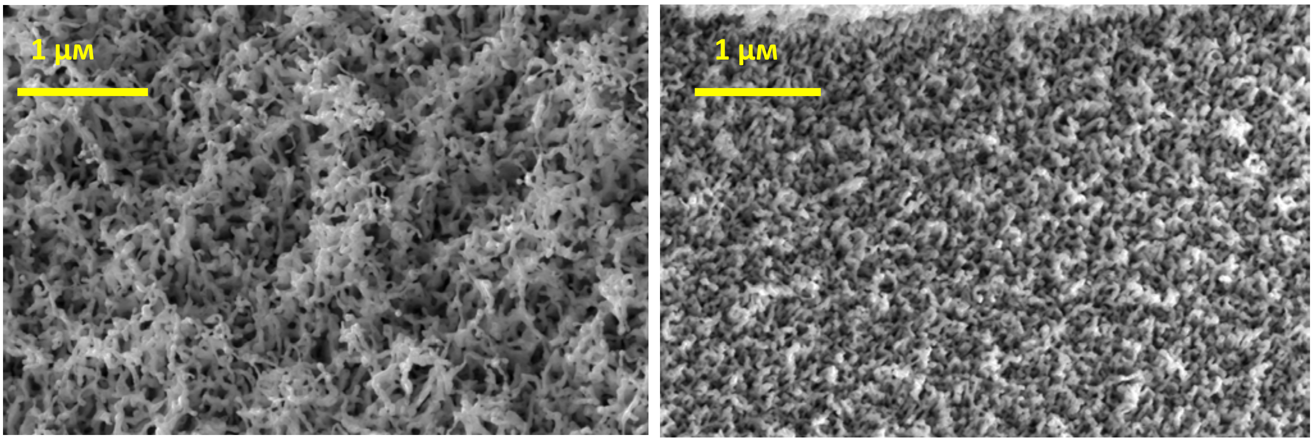

Fig. 1. Fuzzy tungsten structures

PROTOTYPE ELECTROPLASMA INSTALLATION FOR THE GASIFICATION OF ORGANIC WASTE TO PRODUCE FUEL GAS *

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The description of the laboratory electroplasma installation (EPI) created for the processing of organic waste is given by us. It is based on a plasma electric furnace with a 50 kW electric arc plasma torch and ecological synthesis gas purification unit. The capacity of the EPI for waste is 20 kg / h.

Initial data were obtained for the development of a prototype EPI based on the thermodynamic calculations of plasma processes for gasification of organic waste in the temperature range of 300-3000 K. The setup was added to experimental stand of the Institute for the Study of Electric Arc Plasmatrons of Various Purposes in the presence of power sources, compressed air, water-cooling systems, system equipment etc.

As an example the results of the gasification of sawdust and waste polyethylene production are given. The waste was fed into the reaction zone of the electric furnace, followed by pushing the packs with the hydraulic drive rod. The packaged form weighing 1-2 kg each. The temperature in the gasification zone was 1200-1300 °C. Then, the resulting synthesis gas entered the centrifugal-barbatage apparatus (CBA) for quenching of reaction products and purification from solid particles. The further route of the gas is a bag filter, a gas afterburner, cooling and emission through the ventilation system to the atmosphere. Throughout the gas path, thermocouples and a gas analyzer are used to measure the temperature and composition of the fuel gas (synthesis gas).

The experimental data were compared with the results of calculations. For used waste, good correlation was obtained for caloric value of synthesis gas.

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INFLUENCE OF ARCHITECTURE COATINGS BASED ON INTERMETALLIDES, CARBIDES, OXIDES AND NITRIDES OF TI-AL SYSTEMS ON THEIR PHYSICAL AND MECHANICAL PROPERTIES *

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The development of wear-resistant coatings for metal-cutting tools is an urgent task. Research into the formation of wear-resistant multilayer coatings on the surface of hard alloys will provide scientific and technical results and create technologies that are the basis for the innovative development of the domestic market for tool products and increase the competitiveness of domestic tools.

Widespread in the field of hardening tools received a method of applying wear-resistant coatings from the plasma of a vacuum-arc discharge. Because Thanks to this method, it is possible to synthesize a coating on the surface of the instrument, the properties of which cannot be obtained in bulk materials. In this regard, great attention is paid to the development of new coating materials that will improve the physical and mechanical properties and increase tool life.

In the framework of this work, studies of the effect of technological parameters (arc discharge current, bias voltage, pressure) on the phase composition of coatings based on intermetallic compounds of the Ti-Al system synthesized in the medium of various reaction gases (O, N, C) from vacuum arc discharge plasma were conducted. For this purpose, samples of material R6M5 were coated with different architecture. The microstructure of the coatings is shown in Figure 1.

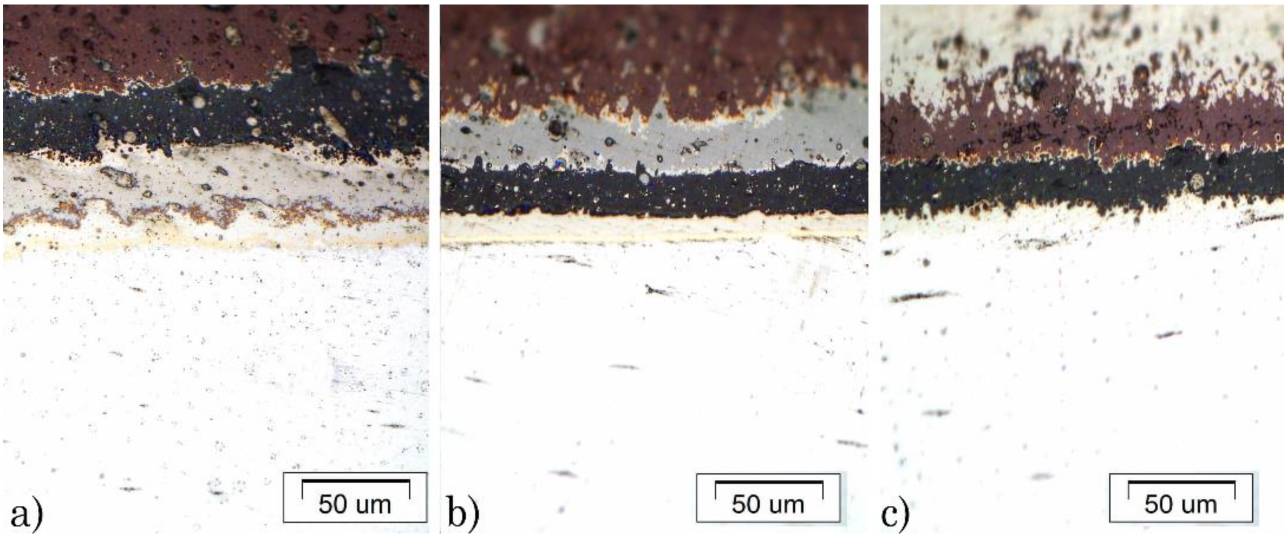

Fig. 1. The microstructure of coatings based on intermetalides, carbides, oxides and nitrides of the Ti-Al system with different architecture

The paper presents the results of studies of the influence of architecture (thickness, chemical composition of layers) of coatings based on intermetallics of the Ti-Al system synthesized in the medium of various reaction gases (O, N, C) on their mechanical and operational properties (microhardness, wear resistance). Based on the results, the architecture of coatings was determined, which has the best physical and mechanical properties.

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NANOSTRUCTURE FORMATION OF HYPOEUTECTIC SILUMIN BY ELECTRON-ION-PLASMA METHODS*

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Recently the attention of the researchers in the field of physical material science is focused on the analysis of the nature of the surface hardening of metals and alloys under the effect of the concentrated fluxes of energy. Among the different widely distributed types of effect the electroexplosion ion plasma alloying (EEA) occupies a special place. It possesses a number of advantages including those due to the formation of nanodimensional structural phase states at the pulsed regime of high-speed heating and cooling of the surface layer. Nowadays, the promising method, from the positions of nanostructurization, is the application of high intensive pulsed electron beams of submillisecond duration. It makes possible to heat under control the surface layers tens millimeters thick in the pulsed regime practically without changing in the structural phase state of the main volume of the material.

The purpose of the research is to analyze the elemental and phase composition, the state of the defect structure of hypoeutectic silumin subjected to the complex processing combining the electroexplosion ion plasma alloying and the subsequent irradiation by the intense pulsed electron beam.

The hypoeutectic silumin AK10M2N was used as a test material. At the first stage the electroexplosion ion plasma alloying of samples by the yttrium oxide powder was carried out using the following regime: the aluminium foil mass – 58.9 mg; Y_2O_3 powder mass – 58.9 mg; the discharge voltage – 2.8 kV. At the second stage the alloyed surface of the samples was irradiated by the intense pulsed electron beam at the plant SOLO. The following parameters of electron beam were used: the energy of the accelerated electron – 17 keV, the energy density of electron beam – 35 J/cm^2, the pulse duration – 150 μs, the number of pulses 3, the pulse repetition rate – 0.3 s^{-1}, the pressure of the residual gas (argon) in the working chamber of the plant – $2{\cdot}10^{-2}$ Pa.

In the cast state the silumin structure is characterized by the presence of a large number of the inclusions of silicon and intermetallides of various shapes and submicron dimensions, the availability of pores revealed by the methods of optic and scanning electron microscopy. The complex processing of silumin results in the transformation of the structure of the samples' surface layer.

The cardinal transformation of the structure of the material's surface layer ≈ 70 μm thick consisting in the dissolution of silicon inclusions and intermetallides of micron and submicron dimensions characteristic of the cast silumin and the formation of the gradient multielemental submicro- nanodimensional structure has been revealed. It has been found that the modified layer has the structure of the high-velocity cellular crystallization and contains the inclusions of the faceted shape whose relative content decreases when moving away from the surface of modification. It has been shown by the methods of micro-X-ray spectral analysis that the surface layer of silumin is a multi-elemental one and along with the atoms of the initial material (aluminium, silicon, copper, nickel, chromium, iron) it is additionally enriched by the atoms of titanium, yttrium and oxygen. It has been established that the cells of high velocity crystallization are enriched by aluminium atoms and the interlayers separating the cells are enriched by silicon atoms. The inclusions of the faceted shape are enriched by the atoms of titanium, aluminium and copper and the interlayers along the boundaries of the inclusions contain, mainly, the yttrium atoms. The performed electron – microscopic microdiffraction analysis shows that the inclusions of the faceted shape are formed by the phase Al_5CuTi_2. Along the boundaries of these inclusions the interlayers having the phase composition of AlCuY are found. It has been revealed that the interlayers of silicon located along the boundaries and in the junctions of the boundaries of the crystallization cells formed by the solid solution based on aluminium have a nanocrystalline structure with the crystallite dimensions varying within 10-20 nm.

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EVOLUTION OF STEAM AND PLASMA PLUME GENERATION ON PULSE LASER ACTION ON THE SURFACE OF METAL IN WATER

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The radiation of the GOR-100M ruby laser (λ = 0.694 mm) operating in the free oscillation regime (pulse duration ~1.2 mc) passed through the focusing system and was directed onto the sample that was mounted in water. The radiation spot diameter on the sample with sharp edges was varied in the course of the experiments from 1 to 2 mm. The energy of the laser pulses varied from 5 to 60 J. To study the spatial and temporal evolution of the laser plasma torch in the course of laser radiation action on the sample, we used the method of high-speed holographic motion-picture recording. The sample was placed in one of the arms of a Mach – Zehnder interferometer, which was illuminated with the radiation of the ruby laser (l = 0.694 μm) operating in the free oscillation regime. The transverse mode selection in the probing laser was accomplished using the aperture, placed in the cavity, and the longitudinal mode selection was provided by the Fabry – Perot cavity standard used as the output mirror. The probing radiation after the collimator was a parallel light beam with the diameter up to 3 cm, which allowed observation of the steam-plasma cloud development. The interferometer was attached to the SFR-1M high-speed recording camera, in which the plane of the film was conjugate with the meridian section of the laser beam, acting on the sample, by means of the objective. The high-speed camera operated in the time magnifier regime. The described setup allowed recording of time-resolved holograms of the focused image of the laser plasma torch. Separate holographic frames provided temporal resolution no worse than 0.8 mc (the single frame exposure time) and the spatial resolution in the object field ~ 50 mm.

The experimental results and solution of motion equations of two-component (led and water steam) system gives such results. At the first stage ($t \leq 10\,\mu c$) because of the high density and temperature ($T\big|\, r = r_0 = 7000\,K$) of erosion products plasma motion is similar to observed in air. Here r_0 is plasma plume near treated surface radius. The motion of erosion products is supersonic and practically one-dimensional (radial). Erosion products cool evaporating water. Velocity of bubble board motion is also supersonic. An intensive flow of the led drops from the zone of erosion is typical for this stage.

At the second stage ($10\,\mu c \leq t \leq 50\,\mu c$) the motion of erosion products is also supersonic, but at this stage water steam mass is considerably greater then mass of erosion products in the bubble. Velocity of bubble board $\vec{U}_b$ is under-sonic, velocity of water steam motion $\vec{U}$ is also under-sonic and considerably less $\vec{U}_b$, but $|\vec{U}|$ increases. The motion of two-component (led and water steam) system is radial.

At the third stage ($50\,\mu c \leq t \leq 500\,\mu c$) velocities of all components of the bubble become under-sonic. The system of components of the bubble motion equations can be transformed to linear and solved analytic.

At the forth stage ($t \geq 500\,\mu c$) water steam motion becomes not one-dimensional (radial). Reaching a bubble board the water steam stream moves transversal to bubble board to the treated sample, reaches it, moves along a sample to its centrum, reaches a plume, heats and moves opposite a laser beam together with erosion products. So a stream of water steam moving along a sample to its centrum, don't avoid a melted metal flow out of the crater and froths it. In the zone contact of "direct" and "reverse" streams appear vortexes. These vortexes fill among all bubble. This is the cause of incidental decay of a steam and gas bubble.

ELECTRIC DISCHARGES IN A MAGNETIC FIELD TO CONTROL HYPERSONIC FLOW AROUND BODIES*

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The control of the aerodynamics of advanced hypersonic vehicles is an crucial task requiring new approaches and principles. Under conditions of hypersonic flight for the realization of effective magnetohydrodynamic (MHD) interaction become advantageous. Various experimental and numerical studies have shown the effectiveness of this type of interaction [1-5]. To investigate the possibilities of MHD effects on a hypersonic flow structure, it is necessary to ionize the gas flow. It is possible to create a local region of conductivity of the flow using electrical discharges under experimental conditions. The paper considers the MHD interaction of a high-speed air flow and electrical discharges (high-voltage pulse and high-frequency) in a homogeneous magnetic field when flowing around test models.

The ionized hypersonic flow near a plate, a wedge and a blunt body has been considered. The discharge current between the electrodes is directed across the air flow and across the magnetic field so that the force determined by the product of the electric current density value by the magnitude of the magnetic induction, was directed upstream for the local gas braking. To simulate the MHD interaction in a hypersonic flow, MHD test rig, based on a shock tube, has been used. The test rig allows simulating high-speed flows of various gases with Mach number M = 6-10. When using air, the flow parameters are simulated correspond to conditions at an altitude of 30-50 km. To observe the structure of the flow near the model, an optical schlieren-system with a high-speed camera.

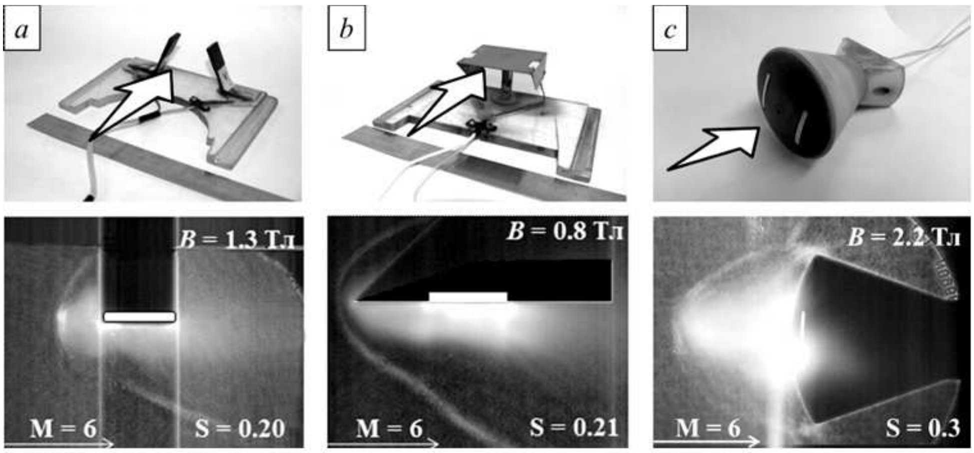

Fig. 1. Photos of the shock waves at strong MHD-interaction near different systems of electrodes.

It is shown, that the use of discharges in a magnetic field makes it possible to significantly change the shock-wave structure of the flow near test models: to change the angle and form of the oblique shock, to generate new shock, to transform attached oblique shock to the bow shock. The bow shock in front of MHD-interaction area near the free streamlined electrodes, the plate model or the blunted body is formed at comparable values of the gyromagnetic interaction parameter S.

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FEATURES AND REGULARITIES OF ELECTRON-ION-PLASMA MODIFICATION OF HIGH-CHROMIUM STEEL*

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The purpose of this work is to establish patterns of formation of the structure and properties of 20Cr23Ni18 steel (similar to the USA – 310 steel), subjected to high-speed heat treatment. Steel 310 is used for the manufacture of parts and mechanisms operating at temperatures up to (1000-1050)°C (parts of the combustion chambers, guide vanes of gas turbines, etc.) [1]. Heat treatment of steel was carried out on the SOLO electron-beam setup with an electron source based on a low-pressure pulsed arc discharge with grid stabilization of cathode plasma boundary and open anode plasma boundary [2]. Irradiation was carried out with the following parameters: the energy of accelerated electrons eV = 18 keV; electron beam energy density E_S (J/cm^2) = 20, 30, and 40; beam pulse duration τ (μs) = 50 and 150; the number of pulses N = 3; pulse repetition rate f = 0.3 s^{-1}; residual gas pressure (argon) in the working chamber ~ 0.02 Pa. The study of structure and phase composition of the material was carried out by the methods of scanning and transmission diffraction electron microscopy.

It has been established that steel 310 in the initial state is a polycrystalline material. Globular particles of the second phase of submicron sizes are located in the volume and along the grain boundaries. The particles are concentrators of stress fields and will lead to the nucleation of fatigue cracks with subsequent destruction of the material. It has been shown that electron beam treatment of steel leads to the dissolution of globular particles and the formation of the structure of cellular crystallization (Fig. 1). Nanoscale (≈ 25 nm) particles of the carbide phase are located along the cell boundaries and stabilize the defective substructure of the material. Performed tests have shown that prior irradiating steel 310 surface with a pulsed electron beam leads to a more than twofold increase in the fatigue life of the material.

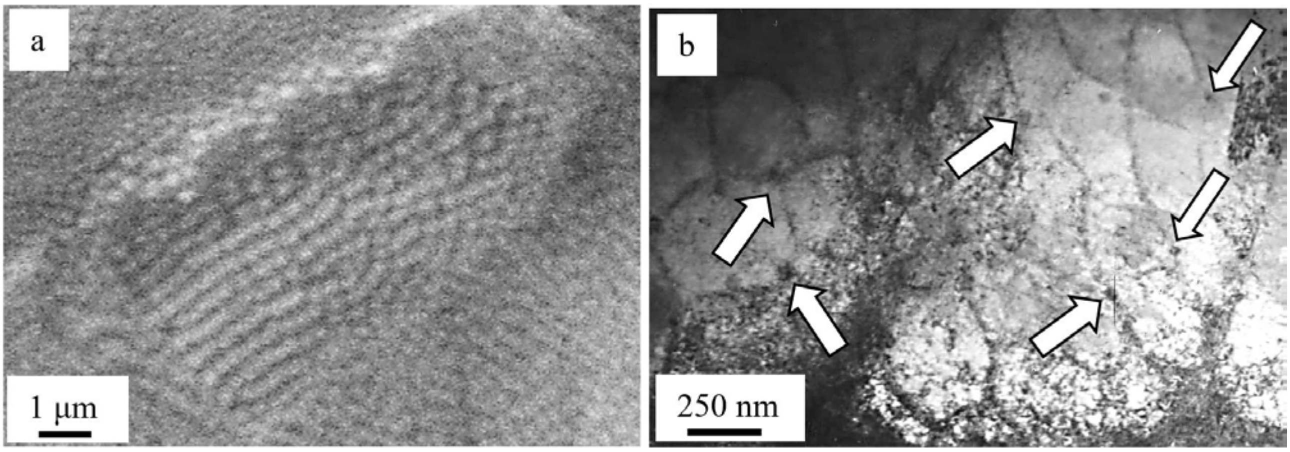

Fig. 1. Electron-microscopic image of surface layer structure of steel 310, irradiated with an electron beam. The arrows indicate particles of the carbide phase, located along the boundaries of the cells of high-speed crystallization. Irradiation mode: 30 J/cm^2; 50 μs; 3 pls.

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DEPOSITION TISICN-COATINGS BY RF MAGNETRON SPUTTERING OF TITANIUM IN AR/N2/((CH3)3SI)2NH *

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TISICN coatings, as is known, are capable to provide high protective properties at the expense of high hardness till 40-50 GPa and at their self-lubricating. High hardness is achieved by forming nanocomposite nc-TICN and nc-SIC in amorphous matrix a-C and SI3N4 [1]. An analysis of the literary data showed the greatest microhardness is usually achieved at an chemical elements ratio TI:SI:C:N ~ (45-40):(2-13):(25-35):(20-25) at.%. The present work was aimed to receive such four-component coatings at more lower temperatures by sputtering of required metal in activated gas environment of technological, accessible, cheap and ecological pollution-free Si-containing materials and afterwards to investigate this films. Titanium was deposited (~0.8 μm/h, ~1 h) by RF magnetron (400W) at total pressure ~ 0.5·Pa with simultaneous decomposition of gas mixture (hexamethyldisilazane 0.4-11 sccm, nitrogen 10-100 sccm and argon up to 80 sccm) by plasma of low energy electron beam of discharge with hollow self-heating cathode and distantly placed anode (40 cm) generated in DC (20 A) or pulse-periodic (50 kHz) mode <8-12 A>. Temperatures of using samples (quartz glass and stainless steel) were ~150 and ~500ºC, maintained by additional heating of holder. The thickness of TISICN films was 0.3-10 μm.

The application of the discharge with self-heating cathode does not influence on current-voltage characteristic of magnetron discharge that does not allow to lower gas demand. The plasma composition was tested by an optical spectroscopy: the intensity of hydrogen H*(652.6 nm) lines in plasmas of magnetron discharge 400W or one with heating cathode (12A) was about equal, i.e. initially ((CH3)3Si)2NH decomposition by both discharges was approximately identical. Also there was measured the thickness and microhardness of coatings, infra-red and X-ray diffraction spectroscopy were carried out.

The microhardness of coatings rose as increase the substrate temperature and at applying to the holder high-frequency (50 kHz) bias voltage U_b=100 V. Increasing of U_b up to 200 V led to reducing of that.

Optical microscopy shows films obtained at high nitrogen partial pressure are the strongly non-uniform and multiphase. The coatings on glass substrates have more homogeneous and smooth structure and possess by the greater microhardness.

An analysis of infra-red spectra allows to suppose, that both factors: increase of temperature and application of assisting discharge, as a rule, result in reduction a background signal of an absorption spectrum, included peaks from meta-stable atomic bonds, and minimizing of bonds being typical for an initial precursor molecule. Besides the absorption peaks of bonds SiC (670-706 cm^{-1}) and SIN (1100 cm^{-1}) amplified and ones of CN, SIH (2200-2300 cm^{-1}) and NH (3350-3380 cm^{-1}) diminished. The observed peaks close to 3800, 1700, 2600 cm^{-1} may be connected with bounds of hydroxyl groups OH. The growth of temperature led to forming reflecting films at the equal fixed small precursor flows. Such spectrum modification testifies about preferential bonding of carbon and nitrogen in TiCN.

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INTENSIFICATION OF PROCESS OF DISSOLUTION OF SOLID SODIUM SILICATE ELECTRICAL DISCHARGES

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Currently, there are two main methods for producing liquid glass – autoclave and autoclave. The most productive way to obtain liquid glass is autoclave method. The main device in this technology is a rotating autoclave, which is a complex and cumbersome engineering structure.

Traditional methods of producing liquid glass have significant disadvantages. For example, the autoclave method involves the use of complex equipment equipped with a rotation drive, and the process itself requires high operating parameters – pressure and temperature. A sharp steam generator is required in the process production chain. In cases where the resulting product does not meet the required density, evaporators are used. They have low efficiency due to a small evaporation surface, and the evaporation process is energy-consuming [1].

Autoclave-free dissolution also has a significant disadvantage - namely, the starting material must be small, which requires grinding equipment. In addition, the autoclave-free dissolution of silicate blocks produces a significant insoluble residue.

The proposed technology for producing liquid glass – electric discharge [2], has a number of advantages over traditional. Electric discharge is characterized as a high-intensity process with a high concentration of energy. This is achieved due to the small time of electric discharge processes in the electric discharge channel and its small spatial dimensions.

Production time of liquid glass is an important technological and economic parameter. In the conditions of industrial production of liquid glass the main controlled parameter is its density. The process of producing liquid glass ends when the desired density is reached. Fig.1 the dependence of the density of liquid glass on the time of dissolution of silicate blocks for two methods of its production – electric discharge (ERS) and autoclave (Autoclave) is presented.

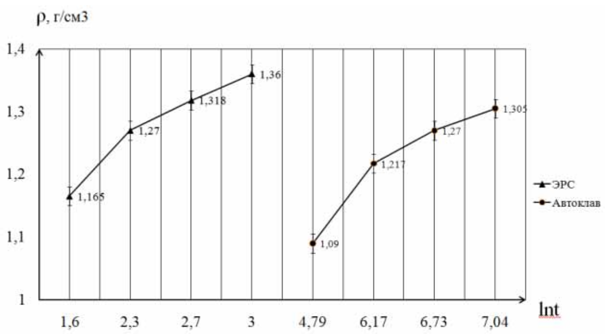

Fig.1 Dependence of the density of liquid glass on time

It follows from the presented dependences that the time of dissolution of a silicate block in a laboratory electric discharge reactor is 56 times less than the time of its dissolution in a stationary laboratory autoclave. The comparison was made for the obtained liquid glass with a density of 1.27 g/cm3.

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FORMATION OF BULK WC_{1-X}-BASED COATINGS ON METAL SUBSTRATES AT HIGH-SPEED SPUTTERING OF ELECTRIC DISCHARGE PLASMA JET*

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Since R.B. Levy and M. Boudart [1] has theoretically proved that tungsten carbide has catalytic properties similar to those of the platinum group metals for some chemical reactions, scientists have actively begun attempting to use it as a catalyst for the hydrogen production. It is known that the widely used hexagonal phases WC and W_2C, as well as the metastable cubic high-temperature modification WC_{1-x} ($0<x<0.42$), can be formed in the W-C system [2]. The main obstacle in the way of studying this cubic phase is the difficulty of its obtaining compared to the hexagonal W_2C and WC phases (narrow synthesis temperature range from ~ 2790 K to ~ 3060 K; transition to a hexagonal structure at slow cooling). However, there are some reports about the possibility of existing WC_{1-x} at room temperature [3], as well as it is believed that it can be obtained from the melt [2] with a crystallization rate of at least 10^8 K/s [4]. In addition to an ambiguity in the issues of obtaining the cubic tungsten carbide phase (WC_{1-x}) in the form of powdered materials, there is a difficulty in obtaining a bulk sample, consisting in the phase transition from a cubic to a hexagonal lattice at a temperature above 700-800 °C [5]. This is one of the main obstacles and the reason why the bulk material has still not been synthesized and, accordingly, its structural, physico-mechanical, thermal and electro-physical characteristics have not been investigated.

Overcoming the above-mentioned obstacles of obtaining and studying WC_{1-x} powdered material is possible by implementing a synthesis process in a high-speed plasma flow containing carbon and tungsten atoms and generated by using a high-current (up to 10^5 A) pulsed (500 μs) coaxial magnetoplasma accelerator of an electric erosion type. The distinctive features of the considered system are a high crystallization rate (10^7-10^9 K/s) and the versatility that allows synthesizing various materials (carbides, nitrides, oxides) in ultrafine form. The preliminary exploratory studies have already shown the possibility to synthesize the nanoscale cubic phase of tungsten carbide by this method [6].

This work presents the studies on the implementation of plasma dynamic method to create bulk coatings, predominantly containing cubic tungsten carbide, on the surfaces of metal substrates. It is found that using the plasma dynamic method it is possible to reach the yield of the WC_{1-x} phase in the coating structure of 85 wt. %. Such sufficient concentration of the WC_{1-x} phase allows estimating its physico-mechanical properties and completing the information about materials in the "W-C" system.

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MICRO-PLASMA ELECTROLYTIC TREATMENT OF THE METAL SURFACE: PROPERTIES OF COATINGS, THEIR APPLICATION

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Microplasma treatment of metals in electrolyte solutions by pulsed currents is one of the most promising, intensively developed methods for obtaining functional oxide coatings on aluminum alloys. Oxide layers can be formed by oxidizing the base material and by thermochemical transformations of electrolyte components and their subsequent melting on the surface of the part. The obtained MAO coatings of MANEL company are not inferior in their properties to ceramics and surpass the oxide coatings obtained by anodizing. The paper offers an overview of the results of tests and applications of MAO coatings of MANEL company.

THE POSSIBILITY OF APPLYING RUNAWAY ELECTRON PREIONIZED DIFFUSE DISCHARGE FOR SYNTHESIS OF DIAMOND, DIAMOND-LIKE COMPOUNDS AND GRAPHENE*

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Interest in the study of electric discharge due to the possibility of its use in various fields of human activity has not weakened for many decades. Until now, one of the main factors influencing on the classification of the types of discharge was the pressure of the ionized gas. Fairly recently, because of the development of technologies a new factor has appeared which one gives a possibility to redefine the existing classification and allows research to be targeted at the looking for a new types of electric discharge. This factor is the duration of lifetime or evolution of the electric discharge. In particular, a discharge occurring as diffuse discharge, independent of the pressure and type of the surrounding gas, was predicted and then realized – a runaway electrons preionized diffuse discharge (REP DD) [1,2].

For more than fifteen years our laboratory has been researching this type of discharge. Today the laboratory has implemented many experimental setups for the study of various characteristics of this discharge [3-5]. Also one of the tasks is to find opportunities for its practical applicability. It is already known that treatment by this type of discharge has a weakly penetrating effect into the surface of materials. So it is possible to use REP DD for fine surface cleaning of damage critical materials [5].

It is known that electric discharges are used for the synthesis of hydrocarbon compounds, diamond-like coatings and diamonds [6]. Theoretical calculations have shown that the energy characteristics of a runaway electrons preionized diffuse discharge make it possible to use this one in such synthesis process, but the efficiency will be very low. However, due to the relatively low energy deposition, it is feasible to produce materials with a high degree of purity and uniformity.

In a mixture of hydrogen and methane it is possible to synthesize diamond-like/diamond films using a REP DD, because it forms atomic hydrogen in a low-excited state required for etching non-diamond forms of carbon and CH-radicals which are necessary for the deposition of crystalline carbon with sp3-hybridization of carbon bonds. Heating of the substrate caused an increase in the homogeneity of the discharge. This paper presents the first results of the possibility of synthesis of carbon compounds under the action of REP DD depending on the gas pressure and concentration of its components.

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MOLYBDENUM CARBIDE EMBEDDED INTO CARBON MATRIX SYNTHESIZED BY DC ARC PLASMA *

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Molybdenum carbide is one of the most important material among metal carbides because of its unique physical and chemical properties such as good resistance to corrosion and oxidation, high abrasion resistance, relatively high electrical conductivity, high melting point, high hardness [1]. Molybdenum carbide due to its catalytic activity can be used for non-platinum electrocatalyst in order to develop cost-effective hydrogen-evolutions technologies [2]. Traditionally molybdenum carbide is synthesized by carbon and molybdenum (or molybdenum oxide) powder mix annealing at ~1400 °C - 1500 °C. Also molybdenum carbide crystalline phases can be obtained by DC arc plasma generation [3-4]. One of the useful material for catalysis is considered a composite based on molybdenum carbide nanoparticles embedded in to carbon matrix [5] because of possible particles surface oxidation exposed by air and aggregation of pure molybdenum carbide materials.

In this paper the material based on molybdenum carbide Mo_2C nanoparticles embedded into carbon matrix is presented. This material has been prepared by the DC arc discharge procedure. The typical high resolution TEM-image and selected area electron diffraction pattern are presented in the Fig. 1. The particle averaged size is about ~3-5 nm; according to the selected area electron diffraction data these particles are characterized by the structure close to the Mo_2C.

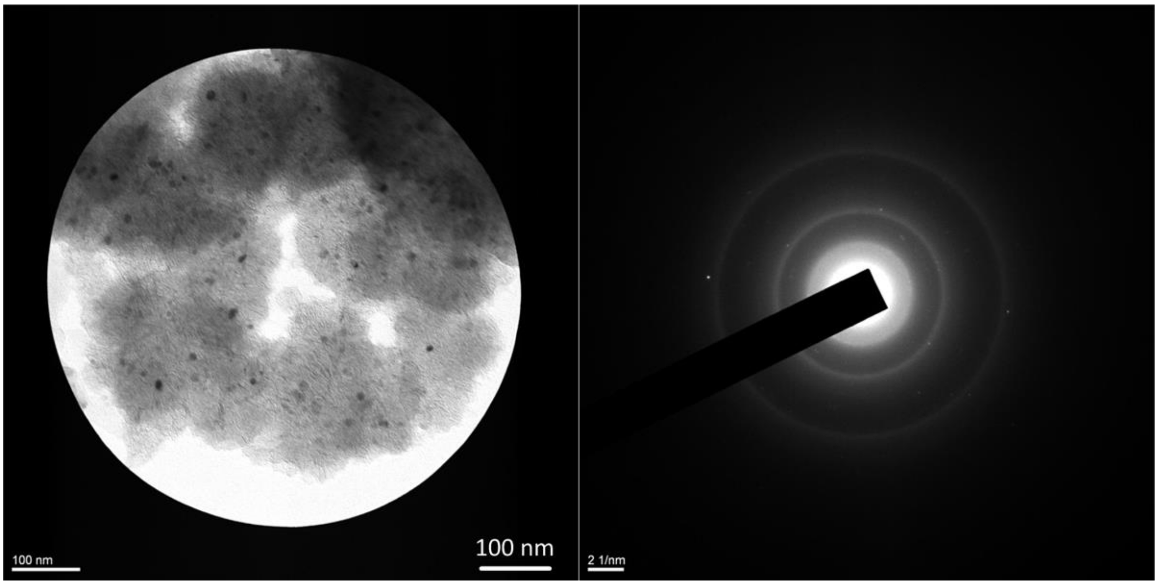

Fig. 1. Typical HRTEM-image and SAED

The arc discharge method is possible to use for molybdenum carbide embedded into the carbon matrix material synthesis. Such material according to the literature data can be useful as a catalyst for the hydrogen evaluation processes.

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MULTI-CYCLIC ELECTRON-ION-PLASMA ALLOYING OF SILUMIN: STRUCTURE, PROPERTIES*

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The aim of the research is to develop a method of high-cycle alloying of silumin samples surface layer by electron-ion-plasma combined method. As a material for the study, AK12 grade silumin (alloy Al-12% Si) was used in the cast state. The alloying of the surface layer of silumin with titanium was carried out by melting the «film (Ti)/substrate (AK12)» system with an intense pulsed electron beam. The thickness of the titanium film in each «deposition/irradiation» cycle was 0.5 μm; number of cycles was 1; 5; 10. Multi-cycle alloying was carried out in a single technological vacuum at the «COMPLEX» setup [1]. The study of the elemental and phase composition, the state of the defective substructure was carried out by the methods of optical, scanning and transmission diffraction electron microscopy. The phase composition and the state of the crystal lattice of the phases were studied by X-ray phase analysis. Mechanical and tribological properties were investigated by determining microhardness, wear resistance and friction coefficient.

It was found that AK12 silumin in the cast state is a multiphase material and contains inclusions of the second phases of various sizes and shapes (Fig. 1, a). Irradiation of the «film/substrate» system leads to the modification of the surface layer up to 160 μm thick with the formation of a structure of high-speed cellular crystallization (Fig. 1, b, c). By methods of X-ray phase analysis it was revealed the formation of intermetallic compounds of $TiAl_3$ and TiAl composition in the surface layer of modified silumin.

It is shown that the microhardness of the modified surface of silumin increases by ≈1.4 times and reaches maximum values after 5 cycles of «deposition/irradiation». Wear resistance reaches maximum values also after 5 cycles of «deposition/irradiation» and exceeds the wear resistance of the initial material by 14.2 times.

It is obvious that high values of the wear resistance of the modified material are due to the release of intermetallic particles in the surface layer.

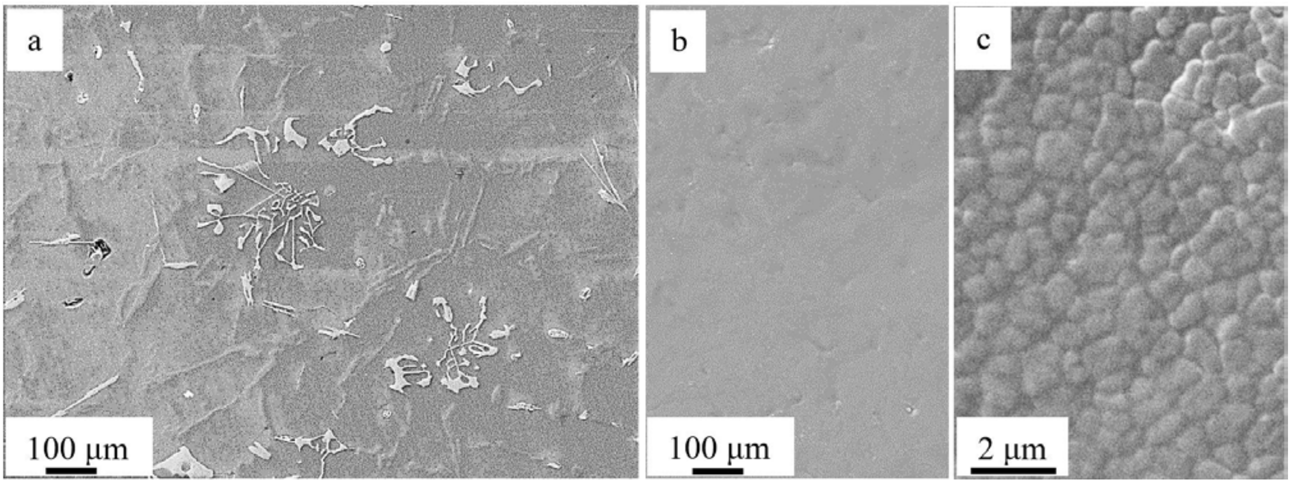

Fig. 1. Electron-microscopic image of AK12 cast silumin structure in the initial state (a) and after modification for five «deposition/irradiation» cycles (b, c).

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NANOSTRUCTURE FORMATION OF HYPOEUTECTIC SILUMIN BY ELECTRON-ION-PLASMA METHODS*

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Recently the attention of the researchers in the field of physical material science is focused on the analysis of the nature of the surface hardening of metals and alloys under the effect of the concentrated fluxes of energy. Among the different widely distributed types of effect the electroexplosion ion plasma alloying (EEA) occupies a special place. It possesses a number of advantages including those due to the formation of nanodimensional structural phase states at the pulsed regime of high-speed heating and cooling of the surface layer. Nowadays, the promising method, from the positions of nanostructurization, is the application of high intensive pulsed electron beams of submillisecond duration. It makes possible to heat under control the surface layers tens millimeters thick in the pulsed regime practically without changing in the structural phase state of the main volume of the material.

The purpose of the research is to analyze the elemental and phase composition, the state of the defect structure of hypoeutectic silumin subjected to the complex processing combining the electroexplosion ion plasma alloying and the subsequent irradiation by the intense pulsed electron beam.

The hypoeutectic silumin AK10M2N was used as a test material. At the first stage the electroexplosion ion plasma alloying of samples by the yttrium oxide powder was carried out using the following regime: the aluminium foil mass – 58.9 mg; Y_2O_3 powder mass – 58.9 mg; the discharge voltage – 2.8 kV. At the second stage the alloyed surface of the samples was irradiated by the intense pulsed electron beam at the plant SOLO. The following parameters of electron beam were used: the energy of the accelerated electron – 17 keV, the energy density of electron beam – 35 J/cm^2, the pulse duration – 150 μs, the number of pulses 3, the pulse repetition rate – 0.3 s^{-1}, the pressure of the residual gas (argon) in the working chamber of the plant – $2\cdot10^{-2}$ Pa.

In the cast state the silumin structure is characterized by the presence of a large number of the inclusions of silicon and intermetallides of various shapes and submicron dimensions, the availability of pores revealed by the methods of optic and scanning electron microscopy. The complex processing of silumin results in the transformation of the structure of the samples' surface layer.

The cardinal transformation of the structure of the material's surface layer ≈ 70 μm thick consisting in the dissolution of silicon inclusions and intermetallides of micron and submicron dimensions characteristic of the cast silumin and the formation of the gradient multielemental submicro- nanodimensional structure has been revealed. It has been found that the modified layer has the structure of the high-velocity cellular crystallization and contains the inclusions of the faceted shape whose relative content decreases when moving away from the surface of modification. It has been shown by the methods of micro-X-ray spectral analysis that the surface layer of silumin is a multi-elemental one and along with the atoms of the initial material (aluminium, silicon, copper, nickel, chromium, iron) it is additionally enriched by the atoms of titanium, yttrium and oxygen. It has been established that the cells of high velocity crystallization are enriched by aluminium atoms and the interlayers separating the cells are enriched by silicon atoms. The inclusions of the faceted shape are enriched by the atoms of titanium, aluminium and copper and the interlayers along the boundaries of the inclusions contain, mainly, the yttrium atoms. The performed electron – microscopic microdiffraction analysis shows that the inclusions of the faceted shape are formed by the phase Al_5CuTi_2. Along the boundaries of these inclusions the interlayers having the phase composition of AlCuY are found. It has been revealed that the interlayers of silicon located along the boundaries and in the junctions of the boundaries of the crystallization cells formed by the solid solution based on aluminium have a nanocrystalline structure with the crystallite dimensions varying within 10-20 nm.

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EFFECT OF PULSE DURATION AND GAS PRESSURE ON DRY REFORMING OF METHANE IN NANOSECOND SPARK DISCHARGE

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Carbon dioxide conversion of methane (or "dry reforming" $CH_4 + CO_2 = 2CO + 2H_2$) is one of the main reactions of plasma-chemical processing of natural gas. Additional interest in this reaction is associated with the possibility of utilizing carbon dioxide in order to reduce the greenhouse effect[1].

For the excitation of the medium in the study of carbon dioxide conversion, various types of discharges are used: such as corona, diffuse, DBD, and spark. In [2] it was shown that when a medium is excited with a short pulse with a duration of 1 ns, the spark discharge has the highest efficiency. Also in [3] it was established that for a diffuse discharge, the degree of methane conversion strongly depends on the pressure of the medium and the proportion of reacting gases. In this paper, dry reforming of methane was investigated when a medium was excited by a spark discharge at various pressures of the gas mixture and discharge pulse durations.

In our experiments, high-voltage pulse generators with output voltage from 50 to 200 kV, pulse duration from 1 to 30 ns, pulse energy from 0.05 to 3 J were used. Methane conversion was studied at pressures from 0.5 to 5 bar for various ratios of methane and carbon dioxide. The main parameters defined were the degree of methane conversion and the specific energy consumption for the conversion of the methane molecule.

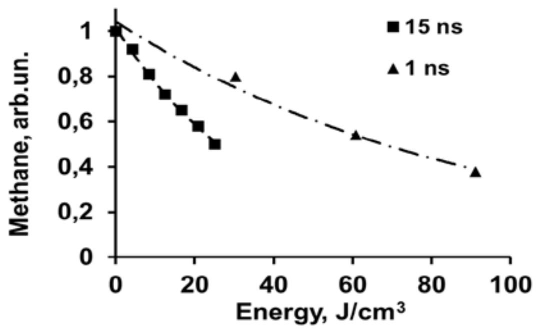

Fig.1. Dependence of methane concentration on the energy input to the gas for discharges with a pulse duration of 1 ns and 15 ns. Pressure is 1 bar, CH_4 / CO_2 mix 1: 1

It has been shown that for a spark discharge, an increase in the duration of the excitation pulse significantly increases the methane conversion efficiency. Figure 1 shows the dependence of methane concentration on the energy input to the gas for discharges with a pulse duration of 1 ns and 15 ns. In addition, as in the case of diffuse and corona discharges, for a spark discharge, an increase in the pressure of the gas mixture leads to a decrease in the degree of methane conversion. The minimum specific energy consumption for methane molecule conversion was about 20 eV / molecule.

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IMPROVEMENT OF EFFICIENCY OF THE USE OF PULSED CORONA DISCHARGE ENERGY DURING THE CONVERSION OF VOLATILE ORGANIC COMPOUNDS*

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The addition of chlorine- and fluorine-containing molecules to gas mixtures, which have the highest electron affinity energy, leads to the most noticeable changes in the properties of discharges and plasma. It is known that conversion of most volatile organic compounds (VOCs) is initiated by electrons with energies sufficient to break certain chemical bonds (most often double) in an organic molecule. When electronegative molecules are added to a mixture containing VOCs, it can be expected that concentration of electrons will decrease as a result of electron attachment processes, and it will lead to a decrease in the discharge current and at the same time to a proportional decrease in the degree of conversion of VOCs. However, experiments on the conversion of VOCs of various types in pulsed corona discharge plasma demonstrated that when CCl_4 or SF_6 is added to the mixture, a decrease in the discharge current and energy input into the gas mixture is observed, but the degree of VOC conversion either remains almost unchanged or even increases [1]. To explain the result obtained, it is necessary to analyze the processes occurring in different regions of pulsed corona discharge. During the formation of pulsed corona discharge in the "wire – cylinder" configuration, three regions can be distinguished, differing in the electric field strength and electron temperature (Fig. 1).

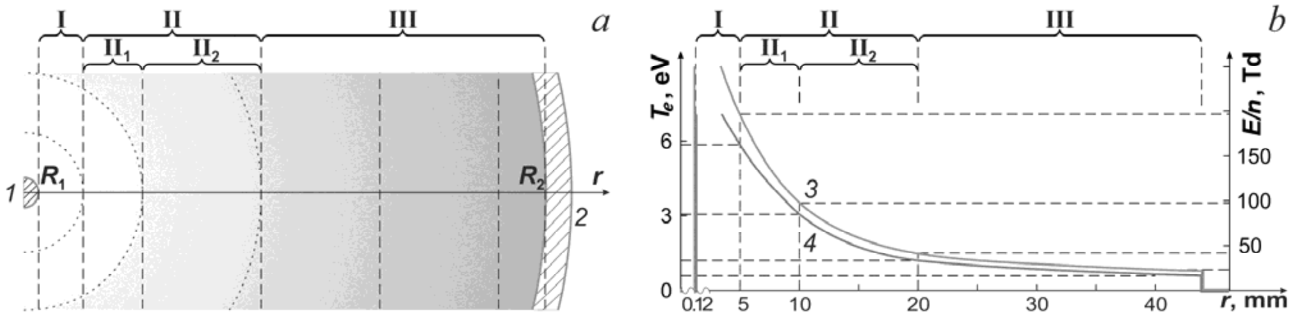

Fig. 1. (*a*) Regions of pulsed corona discharge formed between wire cathode (*1*) and cylindrical anode (*2*). (*b*) Dependencies of reduced electric field strength *E/n* (*3*) and electron temperature T_e (*4*) on the distance *r* from the cylinder axis. I – strong field region; II (II_1 and II_2) – moderate field region; III – weak field region

In region I ionization by direct electron impact, dissociation, and electron excitation of molecules occur, in region II_1 – electron and vibrational excitation of molecules, in region II_2 – vibrational excitation, and in region III – elastic processes and electron drift to the anode. Concentration of electrons in region I reaches $5.6 \cdot 10^{11}$ cm^{-3}. When CCl_4 is added, the processes in region I remain unchanged; however, dissociative attachment additionally occurs in region II_1, and three-body attachment occurs in regions II_2 and III.

The VOC conversion is initiated only in region I, in which attachment processes do not occur. The attachment processes in regions II and III significantly reduce the discharge current and the energy input due to a decrease in the concentration of electrons not involved in the conversion of VOCs, whereas the conversion processes in the strong field region are not inhibited. Comparison of concentration of plasma electrons and changes in concentrations of gas mixture components in our experiments suggests that there are about 20 disappeared tetrachloroethylene molecules C_2Cl_4, about 60 disappeared trichloroethylene molecules C_2HCl_3, and about 10 appeared ozone molecules O_3 per one plasma electron.

Thus, addition of electronegative impurities allows to improve the efficiency of the use of pulsed corona discharge energy during VOCs conversion in atmospheric-pressure air.

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FEATURES OF ELECTRON-BEAM PROCESSING OF METAL-CERAMIC POWDERS IN THE FOREVACUUM

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Currently, the technology of creating materials with varying properties in at least one direction are based either on the synthesis of the entire volume of the material in one cycle – the traditional thermal sintering, microwave sintering, plasma-spark sintering method, etc., or on the creation of the material due to its gradual formation of thin layers - by lamination (LOM), selective laser Sintering (SLS) or melting (SLM) [1]. Each of these methods is applicable to a limited range of materials. The creation of functionally graded materials in one technological cycle by energy impact on the workpiece containing components with a given distribution of the composition in one direction is limited by the difficulty of controlling the impact, which leads to uncontrolled change in properties. In addition, the properties of the synthesized materials in this case directly depend on the properties of its constituent components, the control of which is carried out only at the initial stage of the formation of the product. Thus, the use of electron irradiation with a focused beam in the conditions of active gas medium of the forevacuum range will allow to create functionally graded materials of not only simple, but also complex volume form [2]. The success of the application of the electron beam in the forevacuum for the sintering of ceramics is presented in [3]. For layer-by-layer synthesis of bulk products with changing properties and control of parameters and properties of materials, a narrow-focused electron beam with an energy of 10 keV and a current of 50 mA and a diameter of less than 1 mm was used. As a result of the work, a thin layer of powder material was irradiated, containing aluminum oxide ceramics and titanium in a different mass ratio. Determine the modes of electron beam irradiation allows sintering of metal-ceramic powders in the forevacuum. These results indicate the principal possibility of obtaining by the method of layer-by-layer electron-beam sintering of bulk products from metal-ceramic powder.

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PARAMETERS OF ION STREAM FROM AN ELECTRON-BEAM-PLASMA GENERATED BY A RIBBON ELECTRON BEAM*

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Low-temperature plasma generated by a low-energy electron beam (1-10 Kev) passing through the gas atmosphere of the vacuum chamber [1] is used in various materials processing technologies [2, 3]. The parameters of such beam plasma can be controlled in a fairly wide range due to changes in the current and energy of the electron beam, as well as the composition of the gas atmosphere. The most effective plasma generation occurs at pressures of 5-100 PA – i.e. in the so-called forevacuum range. This paper presents the features of the generation and application of gas ion fluxes from the plasma formation of a large area formed during gas ionization by a ribbon electron beam in the forevacuum pressure range. The influence of electron energy and electron beam current on the concentration of the beam plasma and the current density of the ions extracted from it is determined. The results of materials processing by ion flux from beam plasma are presented.

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HIGH-INTENSITY PULSED ION BEAM GENERATION IN PLASMA EROSION MODE

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The results of a study of the generation of high intensity pulsed ion beam in a diode with a passive anode when operating in a two-pulse mode are presented. When the polarity of the accelerating voltage changes, the plasma erosion mode [1] is realized in the A–K gap, ions are accelerated from the gas plasma, which can ensure the formation of a pulsed beam of gas ions, see Fig. 1.

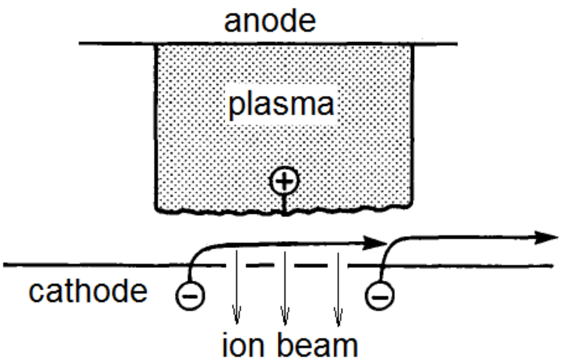

Fig. 1. HIPIB generation scheme in plasma erosion mode

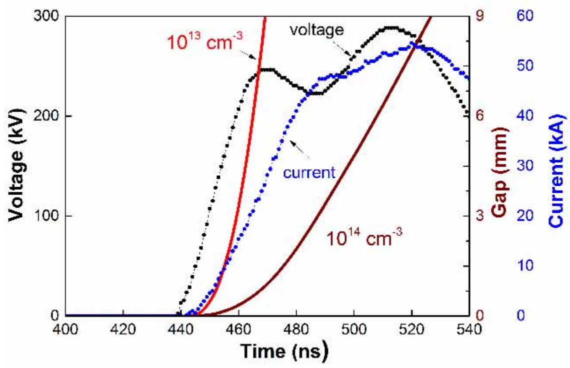

Fig. 2. Waveforms of accelerating voltage (second pulse), diode current and increasing of width of the vacuum gap λ near the cathode at different plasma density (line)

If the width of the vacuum sheath near the cathode in plasma erosion mode increases by an amount of $\Delta\lambda$ in a time of Δt, then the total ion and electron charge removed from the gap is:

$$\Delta Q = 2e \cdot n_0 \cdot S \cdot \Delta\lambda$$

where S - cathode area, n_0 - concentration of gas plasma.

Dividing both sides by Δt, we find the current in the diode:

$$I(t) = 2e \cdot n_0 \cdot S \cdot \frac{d\lambda}{dt}$$

Vacuum sheath near the cathode is:

$$\lambda(t) = \frac{1}{2e \cdot n_0 \cdot S} \int_{t0}^{\infty} I(t)dt$$

Fig. 2 shows the calculation of the vacuum sheath near cathode (λ) during the plasma erosion mode.

The analysis performed showed that in our experimental conditions [2], the concentration of gas plasma in the A-K gap does not exceed 10^{13} cm^{-3} and the pulse duration of the ion current generated in the plasma erosion mode will be less than 20 ns. However, the duration of the ions beam formed by an ion diode is ~200 ns [2]. In addition, the time-of-flight diagnostics of the ion beam shows a good agreement between the experimental and calculated pulse shape of the ion current density [2]. We simulated the signal profile from the collimated Faraday cup provided that the accelerating voltage is equal to the total voltage, applied to the diode. This corresponds to the condition of the acceleration of ions from a thin plasma layer on the surface of the anode, and not from the gas plasma in the A–K gap, see Fig. 1. Therefore, the generation of ions in a diode with a passive anode when operating in a plasma erosion mode is unlikely.

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INFLUENCE OF ENERGY DEPOSITION MODE ON THE EFFECTIVENESS OF THE PLASMA TREATMENT OF WATER IN BUBBLE CHAMBER*

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It is that the non-thermal plasma treatment of liquid (depending on the conditions of the discharge) is based on the simultaneous influence of several physical and chemical factors on the initial liquid: ultraviolet radiation, shock waves, neutral, charged and chemically active particles [1]. The resulting liquid is generally referred to as «plasma-activated». To obtain such liquids, various devices are used, in particular, based on the fact that gas bubbles form in the liquid and a pulsed discharge is ignited. The corresponding class of technical means is called bubble discharge reactors.

In the present work, the influence of coordination of water bubbling process and energy deposition is studied. The setup is including a pulse voltage source with an amplitude of 8-10 kV, frequency from 2 to 50 kHz, pulse front from 20 to 900 ns. This source was connected to a wire anode with a diameter of 0.7-1 mm, located in a dielectric tube and having an internal diameter of 8-10 mm and a narrowing to 1.2-1.5 mm. Air was pumped through the dielectric tube (flow rate up to 5 l/min). The anode, dielectric tube and cathode were placed in water in a dielectric vessel. For matching the deposited energy, the capacity was installed between the cathode and the voltage source.

Voltage pulses from the source were fed to the anode, and at the same time there was an air supply into the dielectric tube, and the liquid was bubbled. As a result, a discharge is ignited between the anode and the interface between the liquid and gas, intensive ionization occurs. Then the chemical species forms and saturate the water as the bubbles move to its surface.

We tested this experimentally using the described setup in case of distilled water treatment. The water was bubbled with voltage pulse repetition rate was up to 50 kHz. Processing was carried out for 2 minutes. The bubbles formation frequency f_b, which was set by the gas flow rate, was determined using an ultra-linear condenser microphone PMC-2 with a three-contact output and a frequency response of up to 20 kHz, close to linear, or using videorecording.

After discharge treatment, the water changed its chemical composition, turning into a solution with new optical absorption spectra. They consist of characteristic NO_3 absorption band in the wavelength range of 200-250 nm. Registration of absorption spectra was carried out by StellarNet EPP2000-C25 spectrometer. The acidity and conductivity of the solution were also monitored.

In the described experiment, water solutions containing NO_3^-ions were obtained. It is known that only this kind of ions provide nitrogen absorption in plants. Then the obtained solutions in tenfold dilution were used for irrigation of flax seeds ("TOST1" cultivar) and wheat ("Irgina" cultivar). Observation of the development of the root system of seeds showed that compared with irrigation with ordinary water, wetting with treated water leads to a 2.5-5 fold increase in the length of the roots of plants and a twofold increase in their dry weight. This is a strong evidence in favor of the industrial applicability of the obtained solutions to stimulate plant growth in agriculture.

It should be noted that for additional matching of energy deposition into the bubble with its life time, it is also necessary to coordinate the electrophysical properties of the liquid with the parameters of the voltage pulses. We assume that the value of the voltage pulse front ρ must be consistent with the conductivity of the liquid ρ as τ [ns] ~ 1 / (1-10·ρ) [μSm/cm] for ρ values from 1 to 1000 μSm/cm. For large values ρ, the discharge treatment process will be inferior to electrolytic methods. This is a physical limitation on the efficiency of the energy input mode in the plasma treatment of water in the bubble chamber.

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* The studies were carried out within the framework of the state assignment of ISE SB RAS on topic No. 13.1.4.

X-RAY MICROANALYSIS OF SILUMIN IRRADIATED BY AN INTENSE PULSED ELECTRON BEAM*

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Al-Si alloys (silumin), due to their low specific weight, relatively high specific strength, good fluidity, belong to cast alloys that are widely used in automotive industry, aircraft-shipbuilding [1]. The presence of coarse inclusions of the second phases, leading to a high brittleness of the material is a clear disadvantage of silumin. The purpose of this work is to establish the patterns of redistribution of alloying elements during irradiation of silumin by an intense pulsed electron beam.

Silumin AK10M2H was used as the study material. Silumin was irradiated at the SOLO setup [2] with the following parameters: the energy of accelerated electrons is 17 keV; electron beam energy density of 35 J / cm2; irradiation pulse duration 150 μs; number of pulses 3; pulse repetition rate 0.3 s-1. Irradiation was carried out in argon plasma at a pressure of 0.02 Pa. The studies of the elemental composition and the state of the defective substructure of the samples of cast silumin and after electron beam irradiation were carried out using transmission diffraction electron microscopy (JEM 2100F).

Using micro X-ray spectral analysis of thin foils, it was established that in cast silumin the alloying elements form inclusions of the second phase of complex chemical composition (Fig. 1, a – c). The dimensions of the inclusions from units to tens micrometers. The irradiation of silumin in the mode of melting of the surface layer is accompanied by the formation of a submicro-sized cellular structure (Fig. 1, d-f). The inclusions of the second phases with sizes less than 100 nm are quasi-uniformly distributed in the volume of the modified layer and are located along the boundaries and in the volume of the cellular substructure. In the aggregate, this change in structure is accompanied by a multiple increase in the microhardness and wear resistance of the material.

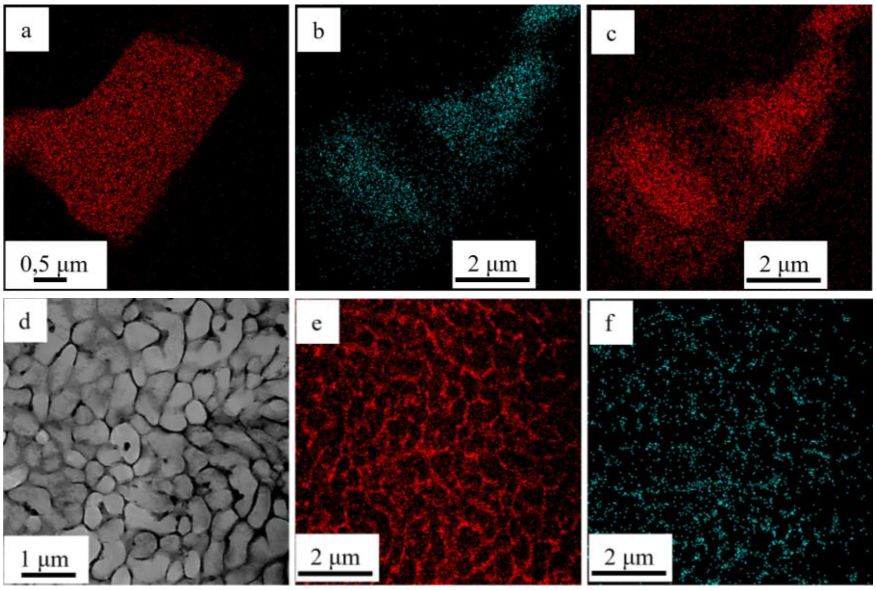

Fig. 1. The structure of silumin in the cast state (a-c) and after irradiation with an electron beam (d-f); images (a, f) were obtained in the characteristic X-rays of silicon atoms; b, f - nickel; c - copper.

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THERMODYNAMICAL ANALYSIS CLINKER FORMATION PROCESSES UNDER THE CONDITION OF LOW TEMPERATURE PLASMA

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Plasma-chemical synthesis of cement clinker is one of the promising methods for cement production [1,2] and is characterized by the intensity, single-stage and complete physical and chemical processes occurring in the liquid phase, which determine the relevance of research in this direction. At the same time, the study and analysis of a set of complex phenomena occurring during chemical interactions and phase formations of clinker minerals are necessary: they provide an opportunity to get valuable information about the methods of targeted reactions, ways of rational management of technological processes and finding new ways to improve the technology of cement production.

Analysis of the obtained results allowed us to establish the thermodynamic probability and the sequence of formation of calcium silicates: the primary compound (about 600 K) in the system is CS (1). This is indicated by the first intersection of the graph with the x-axis at 582 K (309 ºC). Subsequently, the formation reactions of C_3A (6), C_2S (3), C_4AF (7) and C_3S_2 (2) are carried out, in the temperature range of 650–750 K (377–477 ºC). As the temperature rises, the probability of formation of clinker minerals changes: from 708 K (435 ºC), the predominant compound formed during heat treatment is C_2S (3), the synthesis of which is possible on the basis of CS (1). This advantage persists to a temperature of 2180 K (1907 ºC), after which the formation of a C3S compound (4) is most likely. This is indicated by the intersection of the graphs of these reactions and the subsequent increase in the absolute values of the Gibbs energy, which at 3000 K (2727°C) reach 197.6 and 186.7 kJ/mol, respectively, for reactions C_3S (4) and C_2S (3). So in the area 685–2180 K (412–1907 ºC) the probability of the formation of a phase of dicalcium silicate is high. According to the schedule, with an increase in temperature (more than 2180 K), only the phase of tricalcium silicate (4) can exist in the melt, which can be formed on the basis of such minerals as C_4AF (7), CA (5), C_3A (6), CS (1) , C_3S_2 (2) and $CaCO_3$, CaO. Along with this, it was found that the synthesis of C_3A (6) from CA (5) and CaO or $CaCO_3$ is impossible, since the graphs of ΔG change in the formation of these compounds do not overlap. This suggests: the formation of tricalcium aluminate is carried out from the melt, which is consistent with the studies of V.I. Grandma's.

As a result of thermodynamic analysis of the reactions of the synthesis of silicates, aluminates, calcium alumina ferrites, it was found that the use of low-temperature plasma (LTP) for the synthesis of cement clinker is appropriate for the studied mixtures and their C:S ratios. Analysis of the obtained calculations showed that in the traditional temperature range (1000 ÷ 1800 K) the probability of mineral formation and the sequence of reactions with the ratio of oxides in the raw mixtures C: S = 3.32: 1 is preserved and can be located in the following sequence: C_2S, C_3S, C_3S_2 , CS. With an increase in the temperature range under study to 3000 K, the thermodynamic probability of the formation of silicates changes: C_3S, C_2S, C_3S_2, CS. Beginning with 2180 K, C_3S is the most stable compound formed under NTP conditions, which is impossible with the traditional technology (1673–1723 K). Thus, the use of highly concentrated heat fluxes in cement production creates unique conditions for modifying the sequence of chemical reactions during the formation of clinker minerals, and has a positive effect on the quality and properties of the sample being synthesized.

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CREATING A CERAMIC COATING ON METAL*

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The aim of the work was to obtain electrical insulating ceramic coatings on the surface of metals.

The evaporation of ceramics was carried out by a continuous electron beam in a vacuum chamber at a pressure of 5-6 Pa in a residual air atmosphere. The continuous electron beam was generated by a fore-vacuum plasma electron source, the principle of which is based on the emission of electrons from the plasma of a hollow cathode through a single emission channel. Constructive and functional features of this source, as well as its parameters are described in detail in [1, 2]. In the present work, the diameter and length of the emission channel were 1.5 and 2 mm, respectively, at which, during the evaporation process at an accelerating voltage of 18–20 kV, the emission current was 16–30 mA. The diameter of the electron beam on the target was controlled with a single magnetic lens and maintained so that the melting bath forming the vapor from which evaporation takes place fills the entire upper part of the ceramic target. The evaporation process was preceded by a preliminary sintering of the ceramic target, which was carried out by gradually increasing the parameters of the electron beam for 20–25 minutes. The evaporation time at the exposure of the above parameters was 30-60 minutes. Tablets of alumina powder with modifying additives were used as ceramic targets. The deposition rate of the ceramic coating without the formation of a droplet fraction was 50-100 nm / min. Coating thickness 1.5-2.5 microns. The composition of the coating mainly contains aluminum oxide. The contribution of modifying additives is no more than 1-2%.

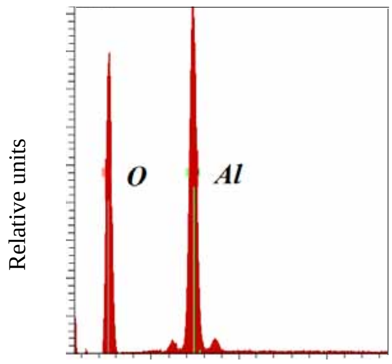

Fig. 1. The composition of the coating

As a result, there is a continuous film containing micro-cracks on the metal surface [3]. In our opinion, this is due to the difference in the thermal expansion coefficients of the metal substrate and the ceramic film during its deposition.

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ELECTROEXPLOSIVE ELECTRICAL EROSION RESISTANT COATINGS OF THE AG-W SYSTEM USED FOR ELECTRICAL CONTACTS OF POWER MINE EQUIPMENT*

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When analyzing the structure on the metallographic cross-sectional microscope of all three samples, the formation of a multilayer structure is revealed, which consists of a low-porosity coating, slightly varying thickness, a liquid-phase alloying layer, and a heat-effected layer. The coating thickness equals to 49.04 ± 0.7 μm for mode 1, 68.5 ± 0.9 μm for mode 2 and 61.26 ± 0.6 μm for mode 3. Coating thickness is measured using the vertical secant method. Coatings in modes 2 and 3 were more uniform in width than in mode 1, which can be explained by the higher temperature of the jet and, therefore, the rate of coating diffusion to cooling was higher. It can be seen from figure 1 that in the first treatment mode, pores of 3 to 30 μm in size are present in the coating. In treatment mode 2, the pore size decreases compared to mode 1. The average pore size in the second mode is 16 μm. In the third treatment mode, the average pore size is 8 μm. Thus, as the absorbing power density increases, the average pore size in the coating of the Ag-W system decreases.

The average value of the layer thickness with the changed state between the coating and the substrate is 14 μm for mode 1, 18.5 μm for mode 2 and 20 μm for mode 3. The width of the layer of the changed state between the substrate and the coating increases as the values of the absorbing power density on the coaxial electrodes increases as well. The analysis of the transition layer between the coating and the substrate showed that the boundary is not even. A zone of mutual mixing of the coating with the substrate is formed. Analyzing the data of the comparative histogram, it can be concluded that the processing mode 2 has the maximum average microhardness of the coating layer, in comparison with other investigated modes. It is 457.5 ± 55.2. In the substrate the microhardness values are smaller than in the coating layer and are 119.4 ± 2.5 HV and 122.0 ± 3.3 HV at a distance of 5 and 40 m from the coating, respectively. It is also important to note that the average microhardness at a distance of 5 μm from the coating for all treatment modes is less than the average microhardness at 40 μm from the coating. It is possible to make an assumption that the reason for this is the heat effect, which is realized when the coating of the Ag-W system is applied by the electroexplosive deposition method. The final stage of the complex study of the regularities in the formation of electroexplosive electroerosion-resistant coatings of the Ag-W system was the atomic force microscopy of the coating obtained in the optimal exposure mode.

The atomic-force image made it possible to establish that the application of coatings of the Ag-W system on the copper contact by the method of electroexplosive deposition in the optimal treatment mode leads to the formation of a structure consisting of a coating, a layer of changed state and a substrate material. The average thickness value of the layer with the changed state located between the coating and the substrate is 16 μm, which correlates with the data obtained in the metallographic analysis.

In the present research devoted to the investigation of electroexplosive coatings of the Ag-W system formed on copper contacts KPV-604, the modes of deposition and the sample weights of Ag-W powder were chosen, coatings were applied by electroexplosive deposition on copper contacts in various modes, metallographic studies for microhardness were carried out and atomic force microscopy of the coatings obtained. The results of microindentation made it possible to reveal the optimum deposition mode (U2 = 2.5 kV), in which the coating layer has the greatest average microhardness value in comparison with other investigated modes. This value is 457.5 ± 55.2 HV, which is 3.8 times higher than the average value of microhardness in the copper substrate. The analysis of the thin section roughness in Mode 2 showed that the average roughness value of the coating is greater than the average roughness values of the substrate and the layer with the changed state by 50.015 nm and 22.849 nm, respectively. Thus, coating of the Ag-W system on copper contacts improves their mechanical and physical properties. The treatment modes studied can significantly increase the microhardness of the surface contact layer, as well as increase their electroerosion resistance due to the presence of tungsten particles in the coating, and also maintain the necessary electrical conductivity due to the presence of silver particles.

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EFFECT OF NITROGEN PRESSURE AND PULSED POWER SUPPLY PARAMETERS ON THE PROCESS OF ION NITRIDING IN GLOW DISCHARGE PLASMA.

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Plasma nitriding has been used in industry for over 30 years and is an alternative to gas nitriding [1]. Important advantages of plasma nitriding are the absence of pollution, high energy efficiency and process controllability [2]. The report presents the results of experiments on hardening the surface of details (steel AISI 5140) using nitriding in a glow discharge plasma. To generate a gas discharge in the fore-vacuum pressure range, a power source was used, which is capable of operating in direct and pulsed current mode. Fig. 1 shows the current-voltage characteristics of a glow discharge that forms at different pressures of nitrogen. As shown in the graph, high discharge power (20 kW) and, accordingly, details temperature (550-580°C) can be maintained over a wide range of operating pressure by varying the discharge voltage and current. In this work, three main regimes were investigated: at low (50–100 Pa), medium (250–300 Pa), and high (500–550 Pa) pressures. The work investigated the influence of the working pressure and electrical parameters of the discharge on the physico-mechanical characteristics of the nitride and diffusion layers. It is shown that the regulation of gas pressure makes it possible to control the length, structure and hardness of diffusion saturation regions in steel. The use of a pulsed power supply allows reducing the arcing at the stage of training and heating of parts, which makes it possible to reduce the total duration of the process.

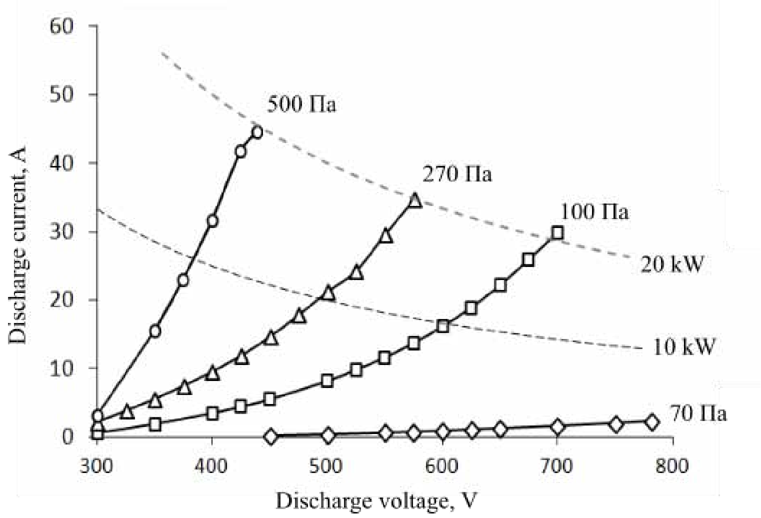

Fig. 1. V-A characteristics of a glow discharge formed in a plasma nitriding system at various pressures of nitrogen in the chamber.

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LOW-TEMPERATURE CEMENTATION OF STAINLESS STEEL IN ELECTRON BEAM GENERATED PLASMA*

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The method of low-temperature (400-500 °C) cementation of 12X18H10T stainless steel by decomposition of acetylene in a wide (100 cm^2) low-energy (200-300 eV) electron beam generated plasma in an Ar+C_2H_2 gas mixture was investigated. The composition of a beam Ar+C2H2-plasma is investigated and it is shown that the degree of decomposition of acetylene varies with the current and energy of the electron beam. It is shown that the magnitude of the flow of acetylene significantly affects the formation rate and hardness of the hardened layer (Fig. 1). From the obtained results it can be seen that at fixed values of argon pressure (~0.8 mTorr), beam current (3.5 A), bias voltage (-120 V), sample temperature (500 °C) and exposure time (3 h) increase in Q_{C2H2} from 1 to 4-5 cm^3/min leads to an increase in the thickness and microhardness of the hardened layer. With a further increase in Q_{C2H2}, an abrupt decrease in the rate of formation of the solid layer occurs. One explanation for the nature of the dependence of the properties of the hardened layer on the acetylene flow may be that for small values of Q_{C2H2} an increase in the growth rate of the layer is achieved due to an increase in the concentration gradient of active particles on the sample surface; particles by ion etching the surface and diffusing carbon atoms into the sample volume. When more active carbon particles enter the surface than are carried away by ion etching and diffusion into the reinforced volume, then a carbon film is formed on the surface separating the active saturating medium from the material being hardened and no layer is formed.

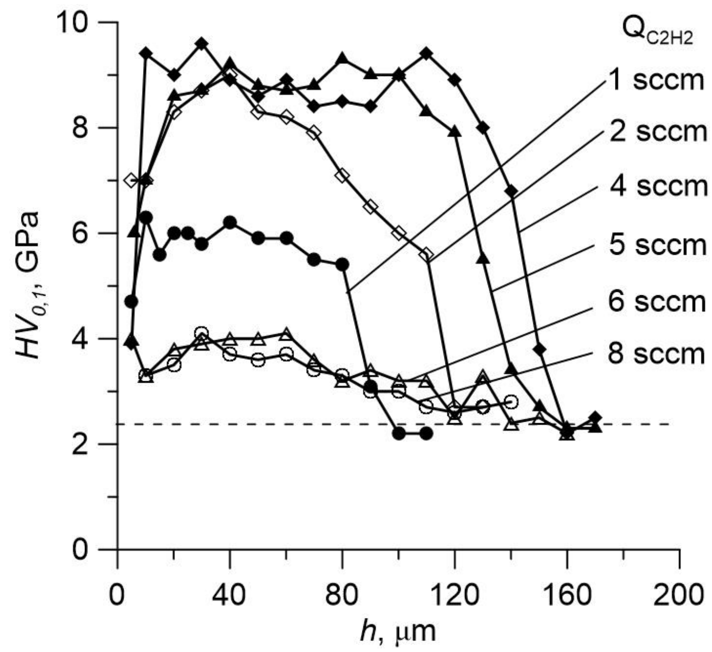

Fig. 1. Microhardness profiles of near-surface layers of hardened samples. The beam current is 3.5 A, the temperature is 500 °C, and the treatment time is 3 hours. The flow of acetylene is 1-8 sccm.

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INVESTIGATION OF THE CONDITIONS FOR THE FORMATION OF SICN-BASED COATINGS IN ELECTRON BEAM GENERATED PLASMA*

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Method of deposition of SiCN-based coatings in a large volume chamber (0.3 m^3) by decomposition of organosilicon precursor (hexamethyldisilazane, HMDS) in nitrogen-argon electron beam generated plasma at pressure of ~1 mTorr at temperaures 200-600ºC was investigated. The analysis of plasma composition by optical emission spectroscopy are carried out. The influence of electron energy (50-500 eV), beam current (10-40 A) and the flow of HMDS (1-10 sccm) on plasma composition and HMDS decomposition degree was investigated. It is shown that the degree of decomposition of precursor molecules in electron beam plasma is higher, than in discharge with self-heated hollow cathode [1]. On the surface of samples made of glass and stainless steel, silicon carbonitride (SiCN) coatings up to 4 µm thick with hardness up to 28 GPa were obtained during 2 hours at 600ºC. Coatings compositions were analyzed by FTIR method that showed that main absorption bands of SiCN(H) system were present in all the spectra (Fig. 1).

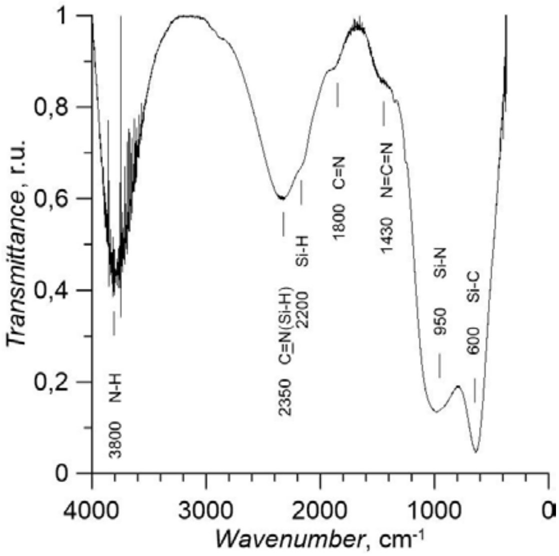

Fig. 1. IR-spectrum of the coating on steel 12X18H10T. Temperature 500ºC, beam current 1,5 A, bias voltage -100V, pressure Ar+N_2+HMDS 1 mTorr (Q_{Ar} : Q_{N2} : Q_{HMDS} =5:1:2).

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CHARACTERIZATION OF NANOSILICA PRODUCED BY ARC PLASMA METHOD

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Obtaining functional nanomaterials is a crucial task of modern science. Silicon dioxide nanopowder (nanosilica) is in demand in various industries and it is advisable to develop new methods for its production.

The research shows possibility of production and characterization of the structural and morphological properties of silicon dioxide nanoparticles obtained by arc plasma method [1-3]. This method allows to use available and environmental friendly natural high-silica materials such as diatomite, quartzite and quartz sand. The arc plasma method is based on physical processes of melting and evaporation of raw material under the influence of thermal plasma of electric arc discharge with subsequent condensation of nanoparticles.

Developed atmospheric pressure DC arc plasma installation was used to obtain the nanosilica. The main structural and morphological characteristics of the obtained nanoparticles were determined. The method of transmission electron microscopy (TEM) was used to study the morphology and size distribution. Brunauer–Emmett–Teller (BET) method was used to study the surface. Energy-dispersive (EDX) and X-ray photoelectron spectroscopies (XPS) were used to determine an elemental composition. The nature of chemical bonding of obtained nanopowder was characterized using a Fourier transform infrared (FTIR) absorption spectroscopy. To study the processes of phase transitions in raw materials after plasma influence, the method of X-ray diffraction (XRD) was used.

The particles of nanosilica obtained by arc plasma method have spherical shape, the size distribution 10-300 nm, the specific surface area 37-71 m^2/g.

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FORMATION OF CATALYTIC LAYERS BY ION BEAM ASSISTED DEPOSITION OF METALS FROM VACUUM ARC DISCHARGE PLASMA*

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Currently, processes of surface modification with the use of ion-plasma technologies are active being developed, which is due to the possibility of a substantial increase in the performance of structural and functional materials without changing the structure and volume properties. The ion-beam modification of functional materials, the properties of which are determined primarily by the surface composition, in particular, of heterogeneous catalysts of chemical reactions, is of great interest [1, 2].

The goal of our research is the preparation of catalytic layers with use of ion beam assisted deposition of active metals from vacuum arc discharge plasma, which is generated in metal vapor.

Catalytic surface layers were formed by ion beam assisted deposition (IBAD) of platinum as basic active metal and one of metals (Ir, Sn, Ce, Gd, Dy, Ho, Yb) as an activating additive. We carried out IBAD mode in which the deposition of the metal and the mixing of deposited layer with the substrate are carried out by accelerated (U = 10 or 5 kV) ions of the same metal [3–10]. Deposition of the metal and mixing of the deposited layer with substrate by accelerated ions of the same metal were performed in an experimental unit, respectively, from a neutral fraction of metal vapor and the vacuum arc discharge plasma of a pulse arc ion source, respectively. A vacuum of $\sim 10^{-2}$ Pa was maintained in the working chamber. Active layers of the electrocatalysts were formed by ion beam assisted deposition of metals onto substrates from valve metals (Al, Ti, and Ta) and carbon materials (glassy carbon, and Toray Carbon Fiber Paper TGP-H-060 T and AVCarb® Carbon Fiber Paper P50 carbon fiber catalyst carriers which are used as material of diffusion layers of membrane electrode assemblies of electrolyzers and fuel cells with polymer membrane electrolyte).

Investigation of the microstructure and composition of layers was carried out by SEM, EBSD, EDX, WD XRF, XPS, and RBS methods. It has been established [3–10] that the obtained catalytic layers are characterized by amorphous atomic structure and contain atoms of the deposited metals, substrate material, as well as impurities of oxygen and carbon; their thickness reaches ~30–50 nm. The content of each deposited metal is several percent by weight. Inclusions of the deposited metals of about several micrometers occur on the surface which is conditioned by metal drops deposition from the arc source; they cover less than 1% of the surface area.

Electrocatalysts with the obtained layers exhibit activity in processes of hydrogen evolution and oxidation of alcohols – methanol and ethanol [3–5, 7, 8]. These processes underlie the principle of operation of alternative hydrogen energy devices: electrolyzers for producing hydrogen and direct methanol and ethanol fuel cells (DMFC, DEFC). Electrocatalysts containing one of rare earth metals (Ce, Gd, Dy, Ho, Yb) as an activating additive exhibit higher activity in oxidation reactions such as ethanol and methanol. A distinctive feature of the resulting electrocatalysts is their higher activity during the oxidation of more complex ethanol molecules compared with methanol, where it is required to ensure the breaking of the C–C chemical bond. Formation of an active surface during the ion beam assisted deposition of the two metals is carried out under vacuum conditions in two steps, which compares favorably with traditional multistage methods for the preparation of supported catalysts based on impregnation of the support with solutions of the compounds of each of the metals, their reduction to the metallic state, drying and etc.

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FORMATION OF THE SILICON COATING ON THE NITI SUBSTRATE BY PLASMA IMMERSION ION TREATMENT[1]

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Thin films and coatings made from silicon on various substrates are widely used in diverse fields of industry, science and engineering. The high biocompatibility of silicon provided use of silicon in medicine as biological sensors and coatings for implants. One of the problems is the deposition of silicon coatings on hard-shaped products such as intravascular stents. The prospect decision for this problem is considered as the using of plasma immersion ion implantation and deposition (PIII&D) method. Because of it, the study of formation mechanism of silicon coatings and their physical-mechanical characteristics by using this method is the topical issue.

In this work, the research of structure and properties of silicon coatings on the nitinol substrate was performed by using PIII&D method depending on technological parameters. The choice of nitinol with nickel content equaled 50,9 at.% is explained that it is used for production of self-expanding intravascular stents. The silicon target with purity equaled 99,999 was used for creation silicon coating. The formation of silicon coating was conducted on device called «SPRUT». This device has plasmatron with thermoemission cathode and magnetron sputtering system with non-balanced magnetron [1]. There is a circle platform for planetary rotation, where the samples of nitinol can be situated in special holders on periphery. The minimum and maximum distances between the samples and the magnetron were 200 and 600 mm respectively. Argon under pressure of 1 Pa was used as an inert gas.

Depending on the mode, the coatings with different thickness were obtained (Fig. 1). It is identified that the main influence on the coating thickness is rendered by the time of treatment and the distance between the magnetron and the substrate. The value of the voltage affects the coating thickness to a much lesser extent: the thickness of coating decreases virtually evenly. The microhardness of coating was from 10 to 15 GPa.

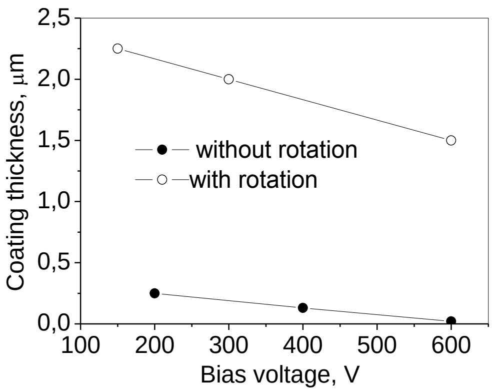

Fig. 1.The dependence of the coating thickness on the value of bias voltage

The value of adhesion toughness of coating and substrate depends on the temperature of prerequisite heating of cover. There was the delamination of coating from substrate during the process of cover formation when the temperature of heating less than 180 °C. The prerequisite heating of substrate up to 300 °C produced good adhesion.

Thus, the using of PIII&D method allows to obtain the silicon coatings on the nitinol substrate in the range of thicknesses from 0.1 to 2.2 µm with good adhesion.

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ABOUT INFLUENCE OF A CHANGE RATE OF A SUBMILLISECOND ELECTRON BEAM ENERGY DURING ITS PULSE ON MODIFICATION OF A STEEL SURFACE*

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The purpose of these studies is to analyze the structure and surface properties of SUS321(12Kh18N10T) stainless steel exposed to a high-current low-energy submillisecond electron beam depending on the change rate of the electron energy of the beam during its pulse. The samples were irradiated with the following general parameters of the electron beam: U_0 = 20 kV, τ = 200 μs, W = 30 J/cm^2, and the different change rate of the electron beam energy during its pulse was achieved by using a different capacitance high-voltage capacitor bank (3 and 12 μF) while maintaining the energy density W of the beam due to a proportional change in the amplitude of the discharge current (the smaller the bank capacitance, the greater the discharge current).

Studies performed by scanning electron microscopy have shown that, regardless of the mode of irradiation, a polycrystalline structure is formed in the surface layer of steel, a characteristic image of which is shown in Fig. 1, a. The structure of high-speed cellular crystallization is revealed in the volume of grains (Fig. 1, b). It was established that the average sizes of grains and cells depend on the mode of irradiation and vary within (3.5 - 10) μm and (230-940) nm, respectively.

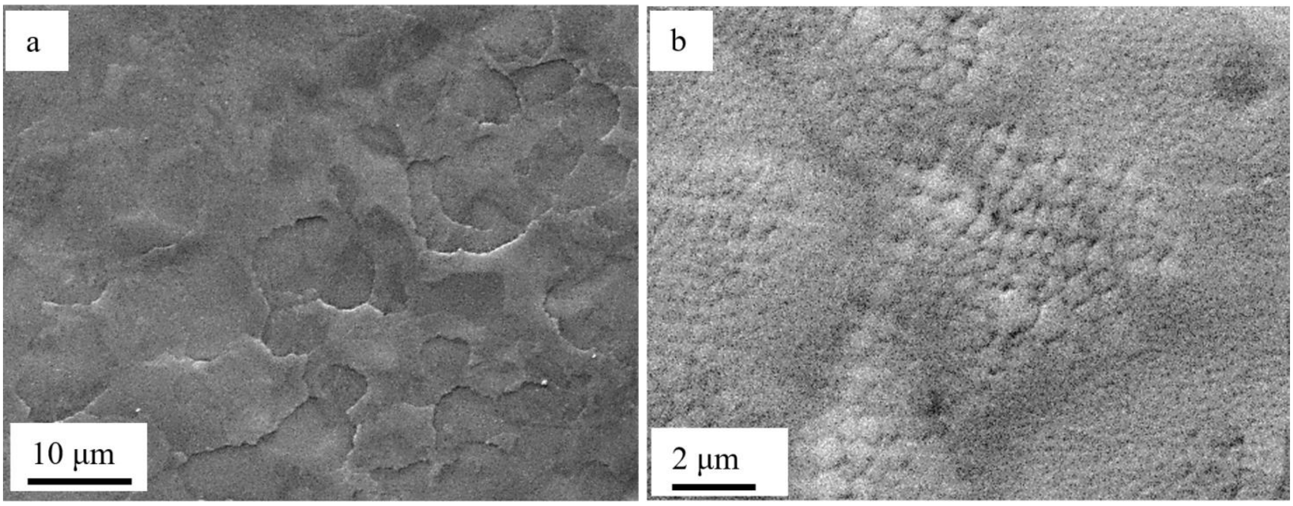

Fig. 1. Electron-microscopic image of the surface structure of samples of steel SUS321 irradiated with a pulsed electron beam.

The results of mechanical and tribological tests showed that the microhardness of the surface layer of steel reaches maximum values when irradiation is occurs by the pulsed electron beam using the battery capacity of C = 3 μF and exceeds the microhardness of steel in the initial state by ≈1.1 times, however, the wear resistance of the material in this case increases by ≈ 2.2 times.

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LOW ENERGY IMPLANTATION OF NITROGEN IONS BY EXTENDED BEAM WITH A BALLISTIC FOCUSING IN A STAINLESS STEEL*

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The results of experiments on the low-energy implantation of nitrogen ions in stainless steel 12X18H10T (analogue of AISI 321) are presented. The processing with a pulsed extended beam of nitrogen ions, obtained using a ballistic focusing system was carried out. The source of ions was the nitrogen plasma of a non-self-sustained gas arc discharge with a thermionic cathode [1]. The formation of a pickling hole on the sample surface as a result of ion etching is shown. The profile of this hole is depends on the parameters of ion beam action. An increasing of surface hardness up to 4 times when processing stainless steel in such system is shown. The hardness increasing is due to the formation of a modified layer in the surface occurs. The layer contains nitrides of iron and alloying elements and its thickness reaches 50 microns. The formation of a modified layer across the processed samples surface, including outside the ion beam focusing region, is shown.

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TRIGGERED GAS SWITCHES WITH A SHARPLY NON-UNIFORM ELECTRIC FIELD AT THE ELECTRODE WITH NEGATIVE POTENTIAL [*]

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The paper presents the design and results of studies for two triggered high-pressure gas switches intended for pulse-periodic capacitive storages with the stored energy level of about 100–1000 J. The operating voltage of the first switch is over 200 kV, for the second switch is up to 50 kV. A feature for both switches is a configuration with a sharply non-uniform field at the electrode with negative potential. In the charging process of a capacitive energy storage, a corona-streamer discharge occurs in the switch, the current of which increases with increasing voltage. Cathode discharge plasma shields a sharp cathode edge and local areas of inhomogeneity with increased emission and also gives a uniform flow of initiating electrons into the gap of the switch. As a result, conditions in the discharge gap vary slightly from pulse to pulse and stabilization of the breakdown voltage is achieved. The triggered switches do not impose strict requirements on the working pressure and has a steady trigger when the air pressure changes by more than 1 atm.

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PROTECTIVE AND ANTI-REFLECTION SILICON-CARBON FILMS FOR IR OPTIC

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1. Introduction

When creating equipment operating in the IR wavelength region, films based on carbon (a-C, a-C:H) are of great interest. They can provide not only high transparency of IR optics, but also protective properties [1, 2]. However, high residual stresses in these films lead to their poor adhesion and the impossibility of forming thick films (>1 μm) [3]. a-C:H films doped with silicon and oxygen (a-C:H:SiO_x) have low internal stresses, and possess good physico-mechanical and tribological properties [4]. In this paper, we have investigated structural, mechanical and optical properties of a-C:H:SiO_x films deposited on Si by plasma assisted chemical vapor deposition (PACVD) method and their thermal stability.

2. Results

The a-C:H:SiOx films were deposited by the PACVD method using a bipolar substrate bias in a mixture of Ar and polyphenylmethylsiloxane vapors. The substrates were single crystal silicon plates with a transparency of about 50% in the IR region (λ = 2-14 μm). The transparency of the samples in the IR region was measured using a Nicolet 5700 FTIR spectrometer. To determine the hardness of films, a Nanotest 600 nanoindenter was used. Raman spectroscopy was used to analyze changes in the structure of the films, in particular, the content of sp3 and sp2-hybridized carbon atoms. The morphology of the films surface was investigated by atomic force microscopy. Properties and the structural behavior of a-C:H:SiO_x films were examined after annealing at various temperatures up to 500 °C.

It is shown that deposition of films on both sides of Si substrate provides an increase in the integral transparency of the sample from 50 to 87% in the in the 3-5 μm spectral region. Wherein, the hardness of the film is about 20 GPa, the modulus of elasticity is 152 GPa, the plasticity index H/E is 0.13, and the resistance to plastic deformation H^3/E^2 is 352 MPa. It is shown that high-temperature annealing up to a temperature of 500 °C does not reduce the integral transparency of the films in the 3-5 μm spectral range, and the film hardness does not change significantly. Although, according to Raman spectroscopy, significant changes occur in the structure of the film after annealing: the location, intensity, width of the D and G peaks, and the I_D/I_G ratio change.

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MEASUREMENT OF THE SURFACE TEMPERATURE OF TICUN COATING / A7 SUBSTRATE SYSTEM AT PULSED ELECTRON-BEAM TREATMENT*

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Surface modification of metal materials and products using pulsed electron-beam processing is widely used in various industries, aircraft and automotive, aerospace and medical technologies, etc. [1-3]. Recently, technologies for surface engineering of materials, combining the application of thin (hundreds of nanometers – few microns) coating films and subsequent liquid-phase mixing with the substrate material using a pulsed electron beam have been developed [3-4]. Thus, it is possible to create surface layers with desired physical and mechanical properties. To fully understand the processes taking place in the surface layer under pulsed thermal effects, it is necessary to know the values and rates of temperature change of the surface being modified. However, direct measurement of the surface temperature by the contact method at pulsed (tens-hundreds of microseconds) heating is not possible. Previously, only numerical methods for calculating thermal fields, which cannot fully take into account all the effects arising in the material, were used to describe such processes. At present, high-speed infrared pyrometers have appeared for contactless determination of the surface temperature of materials with a wide range of temperature measurements (from hundreds to several thousand degrees).

In this work A7 aluminum alloy (substrate)/TiCuN (coating) system was used as samples of 15x15x5 mm size with the coating thickness varying from 1 to 6 μm. The surface of the samples was subjected to a pulsed electron-beam treatment on the "SOLO" vacuum setup [5] (included in complex of unique installations "UNIKUUM"), which is based on a pulsed electron source with a plasma cathode. During irradiation, the following parameters were varied: the energy density per pulse was 5–10 J/cm^2, the pulse duration was 100–200 μs. Such a range of parameters was chosen on the basis of preliminary experiments in order to not destroy the coating (TiCuN begins to deteriorate due to the loss of nitrogen at temperatures above 800 °C). The maximum temperature in the experiments did not exceed 1000 °C, which is significantly higher than the melting point of the aluminum substrate (650 °C). To measure the surface temperature of the samples during irradiation, a high-speed infrared pyrometer "Kleiber KGA 740-LO" with a measurement range of 300-2300 °C was used. The signal from the pyrometer was recorded as an oscillogram of the samples surface temperature dependence on time.

An analysis of the results showed that with increasing coating thickness, ceteris paribus, the maximum temperature reached on the surface of the samples is increases. This is explained by the thermal conductivity of the TiCuN coating and the corresponding decrease in the effect of the aluminum substrate on the heat removal from the surface of the samples. With a decrease in the power density in a pulse (with an increase in the pulse duration at the same energy density in the pulse), the effect of the coating thickness becomes less significant, since the heating rate becomes comparable with the heat removal rate due to the thermal conductivity of the coating, while the maximum temperature remains almost unchanged during the pulse (thermodynamic equilibrium is reached on the surface).

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ADDITIVE MANUFACTURED VT6 TITANIUM ALLOY SURFACE MODIFICATION BY ELECTRON-ION-PLASMA METHODS*

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Purposeful design of the surface of materials and products using modern electron-ion-plasma methods is an important task, since its solution allows to create functional layers and coatings that significantly increase the physicomechanical and performance characteristics of machine parts and mechanisms, as well as a variety of tools, increasing their service life in extreme conditions of operation and thus leading to energy and resource saving [1-4]. A new step in the development of integrated electron-ion-plasma technology, which determines its undoubted scientific novelty and practical significance, is the combination of its constituent processes in a single vacuum cycle: (1) the formation of a gradient multiphase surface layer by introducing elements (nitrogen, carbon, oxygen, etc.), (2) synthesis of thin metal films or superhard nanostructured coatings based on nitrides (carbides, borides, etc.) of refractory metals (TiCuN, ZrMoN, TiSiN, etc.) by ion-plasma methods and (3) formation of surface alloys when mixing a film/substrate system with predicted functional properties or fusing these coatings into the substrate with a high-intensity pulsed electron beam to increase adhesion forces of the coating/substrate system [5].

Works on formation on a surface of the samples of VT6 titanium alloy made by method of additive manufacturing, the film/substrate system with the subsequent mixing by means of a pulse electron beam are carried out. Zirconium film of 2 μm thick was deposited by method of plasma assisted arc in the presence of gas plasma of arc discharge generated by «PINK» plasma generator [6].

Superficial alloying of a substrate with material of the deposited film and finishing processing of a surface was carried out as a result of pulse melting of the film/substrate system by a high-intensity pulsed electron beam.

Mechanical properties of a surface of the modified samples (roughness, microhardness, structure, wear resistance) made by means of additive technologies and irradiated in selected optimum modes in comparison with initial samples are defined. Mechanical tests of samples on stretching are carried out («Instron», model 3369). Regularities of change of structure and mechanical properties of a surface depending on the mode of processing of samples are revealed.

It is shown that alloying of the samples of VT6 titanium alloy made by method of additive manufacturing in a single vacuum cycle on «COMPLEX» installation [5] (included in complex of unique installations «UNIKUUM») by deposition of a thin film of zirconium and the subsequent liquid-phase mixing by means of pulse electron beam treatment allows considerably to reduce roughness and porosity of a surface layer and to increase its mechanical properties. In the optimum modes of processing the increase in microhardness at ≈ 40% in comparison with initial samples has been received. Values of roughness, tensile strength and wear resistance correspond to initial material.

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NANOSTRUCTURING OF THE T31507 STEEL SURFACE BY VANADIUM BORIDES UNDER THE INFLUENCE ELECTRON BEAMS IN A VACUUM

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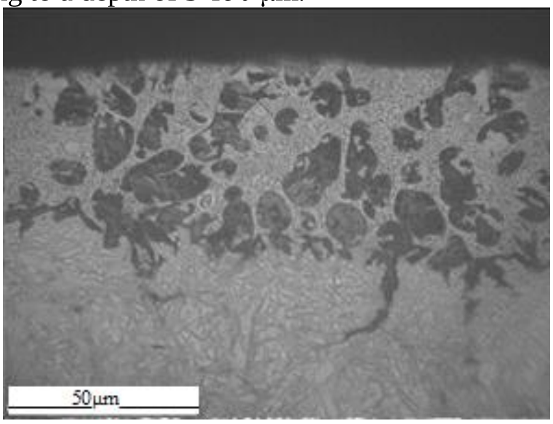
The work discusses the features of surface hardening of T31507 steel under the influence of powerful electron beams, on account of quenching and the formation of layers based on vanadium borides. The most important characteristic of borides, determining their practical use, is their high hardness associated with the directional nature and energy strength of interatomic bonds. The experiments used a vacuum electron beam installation "SOLO", created in IHCE SB RAS, which is based on an electron source with a plasma cathode based on a pulsed low-pressure arc discharge with grid stabilization of the cathode plasma boundary.

Thermodynamic calculations showed that boride V_3B_4 using the stoichiometric mixture V_2O_3-B-C cannot be obtained due to the formation of iron borides Fe_2B, FeB (interaction with the metal base) and borides of alloying elements (CrB_2, WB, MnB_2). The introduction of excess amounts of boron and carbon made it possible to choose the optimal compositions for the preparation of composite layers with the maximum yield of borides. To do this, vary the concentration of B in the mixture of 50-50 (steel – reaction mixture). Will find the maximum flow rate for maximum output V_3B_4 23 wt%.

Analysis of the thermodynamic calculations made it possible to determine the optimal conditions for the interaction of the V_2O_3:B:C reaction mixture with the surface of carbon T31507 steel for forming the composite coating to a depth of 5-150 μm.



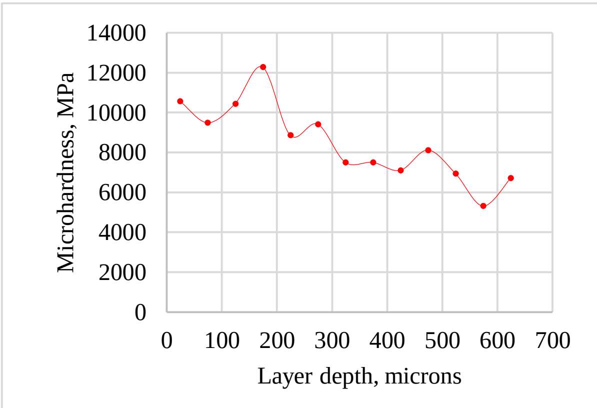


Fig. Structure and microhardness of V_3B_4 layers on T31507 steel ($P = 10^{-3}$ Pa)

After electron beam treatment of the T31507 steel, with boron-containing coatings applied on them, non-uniform layers are formed on the surface, 50-100 microns thick. The resulting layers have a specified thickness of almost the entire length. In fig. it can be seen that various regions are present in the layer, which allows one to conclude that these are particles of borides of alloying elements (tungsten, chromium, manganese, and vanadium). The layer is firmly held on a metal base.

In figure shows the measurement of the microhardness of the vanadium boride layers with a step of 30-50 microns. An uneven distribution of microhardness in thickness was found. However, in all the studied samples, a regular distribution of microhardness was observed depending on the layer thickness. Some very rare inclusions have HV≈13000 MPa and are located in the surface zones of the layer. Layers are characterized by the most complex disordered structure. The chaotic distribution of microhardness in thickness in boride V_3B_4 is explained by the fact that this boride is formed at a lower temperature, and, accordingly, there are very many impurities in the layer.

THERMOPHYSICAL MODEL OF ELECTRON BEAM BORIDING OF CARBON STEEL ST3.

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The work is aimed at developing a thermophysical model of electron-beam boriding of carbon steels.

One of the main tasks for creating a thermodynamic model is to determine the optimal synthesis conditions, in particular the formation temperature at different pressures in the working chamber. It is known that the temperature of formation of iron borides decreases to 800 K with a decrease in the total pressure to 10^{-3} Pa (figure 1). For the experiments, used electron-beam installation with axial gun for thermal cathodes. Reaction daubs of various stoichiometric compositions of Fe_2O_3: 3B: 3C, Fe_2O_3: 2B: 3C were deposited on the surface of the sample. Power density of the electron beam W = 5.7×10^2 W/mm^2, processing time 1-3 min. The experiments were carried out at a pressure of 10^{-3} Pa. Previously, a sequence of chemical transformations occurring in the synthesis of borides was established, namely, "oxides $\rightarrow$ carbides $\rightarrow$ lower borides $\rightarrow$ higher borides". When the highly concentrated energy flows are exposed on the reaction daub, the SHS process is initiated. As a result of SHS, solid combustion products are formed, in particular, iron borides. After the exposure of the electron beam ends, the crystallization process begins, as a result of which a dendritic-like structure of the layer is formed [1].

To simulate the process of electron-beam processing, selected samples have the form shown in figure 2. The electron beam is first focused on the surface of the sample, and then converted into a raster with the help of an electron beam control unit and scanned across its diameter. The calculation of thermal fields was performed using the Maple 18 program. The physical model of the electron beam treatment process is determined by a number of parameters: the power of impact of the electron beam, the speed of processing the details, the time of exposure. Data on the size of the part, the depth of penetration of electrons into the sample are taken into account $S = 2{,}1\times10^{-12}\dfrac{U^2}{\rho}$, the depth of maximum energy deposition $h = 0{,}75\times S$, as well as the thermophysical characteristics of a particular material.

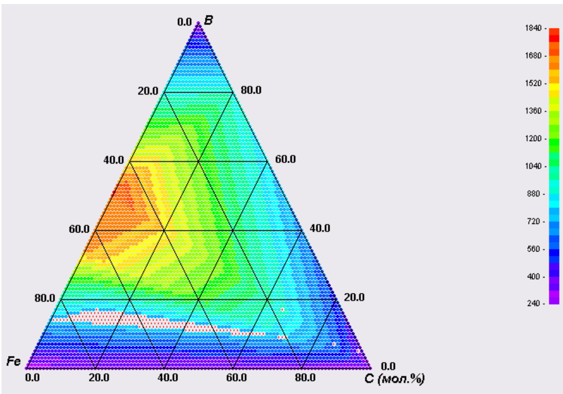

Fig.1. Isotherms in the Fe-B-C system at a pressure of 10^{-3} Pa.

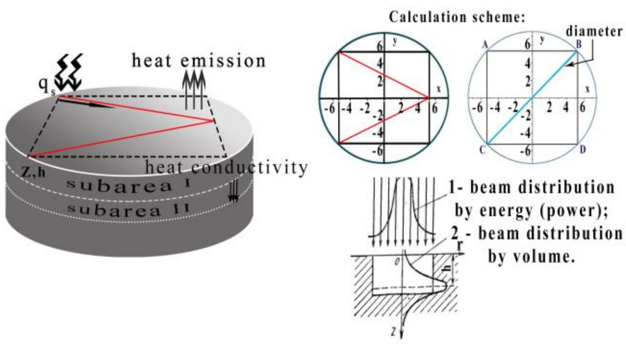

Fig.2 Scheme of energy input to the sample surface.

This paper presents a model for the formation of iron borides, analyzes the thermal processes and considers the phase equilibria of these structures. The strength characteristics of the obtained iron borides layer were investigated.

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PLASMACHEMICAL SYNTHESIS OF FULLERENES C60 AND C70 AT ATMOSPHERIC PRESSURE AND THE EFFECT OF FULLERENES ON THE HYDRATION OF PORTLAND CEMENT

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The article describes the results of the study of plasma chemical synthesis of fullerenes C60 and C70 at atmospheric pressure in high-frequency arc discharge and results of modification cement stone by fullerenes. Composition of carbon soot can be controlled by changing helium pressure. The yield of higher fullerenes increases with increasing helium pressure, while the yield of carbon nanotubes decreases. Elevated pressure reduces the concentration of carbon in the carbon vapor, which leads to increase in the yield of fullerene C60 and higher fullerenes C70.[1,5]

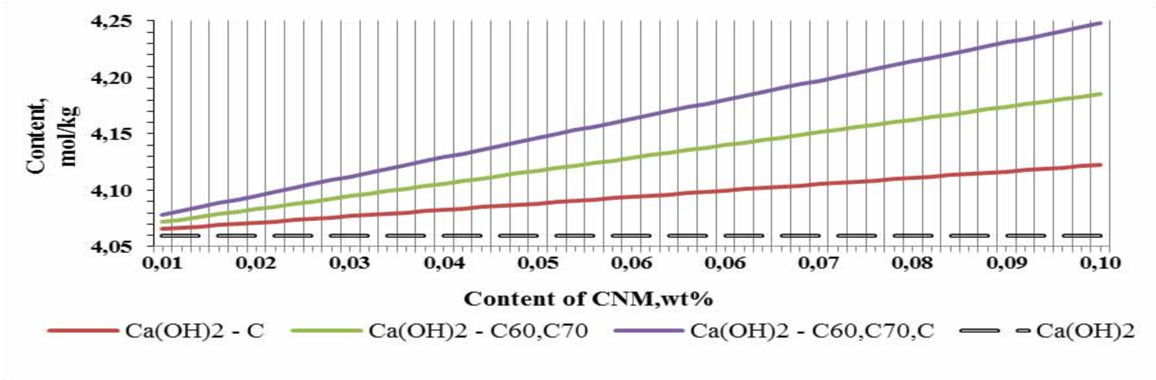

Fig. 1. . Calculated yield of phase Ca(OH)2 from content of CNM in system «cement – H2O-CNM»

Obtained carbon soot was used for modification cement stone for improved physical and mechanical properties. Change in phase composition, structure and properties of modifying cement stone were investigated. The effects of the CNM on the early hydration process of cement were studied using X-ray diffraction analysis and thermodynamic modeling. The CNM were found to accelerate the hydration reaction of the C3S in the cement. In particular, the CNM appeared to act as nucleating sites for the hydration products, with the CNM becoming rapidly coated with C-S-H. The addition of CNM improves the strength characteristics of cement stone because it reduces the porosity of cement stone and building materials based on it. Thermodynamic calculations (Fig.1) were performed in the Terra program [6]. The study of cement stone hydration and structure was performed using X-ray phase analysis and electron microscopic analysis [5]. Thermo-kinetic analysis [4] and thermodynamic modeling revealed a temperature increase of hydration with the introduction of CNM into the cement paste that shows the complete progress of the reactions. The dynamics of reduction of calcium silicate peaks characterizes the activation of the processes of hydration and binding of portlandite, which explains the increase in strength of the modified cement stone. The structure of the cement stone has a high density and uniformity in the introduction of CNM.

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STRUCTURAL FEATURES OF THE MAGNETRON SPUTTERED CUO/GDC FILMS FOR SOLID OXIDE FUEL CELL APPLICATION*

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Solid oxide fuel cells (SOFCs) are promising devices for efficient and environmentally friendly electricity generation. For operation on hydrogen, Ni-containing cermets are usually used as a SOFC anode, since they have a high catalytic activity. But if synthesis gas is used as fuel, Ni shows a high rate of degradation due to poisoning by impurities of sulfur or carbon [1]. Carbonization blocks catalytically active centers, changes the microstructure of the anode and, as a result, reduces the cell performance. In recent studies [2], Cu has been considered as a new material with good electronic conductivity instead of Ni in SOFC anodes. The aim of the present study is to investigate the microstructural characteristics of magnetron sputtered CuO/GDC layers and their changes after reduction in hydrogen atmosphere and heat treatment.

CuO/GDC thin films were formed by the method of reactive magnetron co-sputtering of Cu (99.995% purity) and $Ce_{0.9}Gd_{0.1}$ targets (75 mm diameter). Sputtering was carried out at working pressure of 0.2 Pa (Ar and O_2 flow rates were 26 and 33 sccm, respectively). The discharge power of a Ce-Gd magnetron was 1 kW in all experiments. The discharge power of the Cu magnetron ranged from 100 to 700 W to control the volume content of CuO in the film.

The composition and microstructure of the $CuO/Ce_{0.9}Gd_{0.1}O_{2-\delta}$ (CuO/GDC) thin films were characterized after deposition, annealing in air and reducing atmosphere using energy dispersive X-Ray spectroscopy, scanning electron microscopy and X-ray diffractometry. The as-deposited film consists of cubic fluorite structures of GDC and Cu_2O and has a dense, homogeneous structure (Fig. 1,a). It was shown that, Cu segregation is observed in CuO/GDC films, after reduction in hydrogen at a temperature of 600°C, with the formation of Cu agglomerates on the surface (Fig. 1,b).

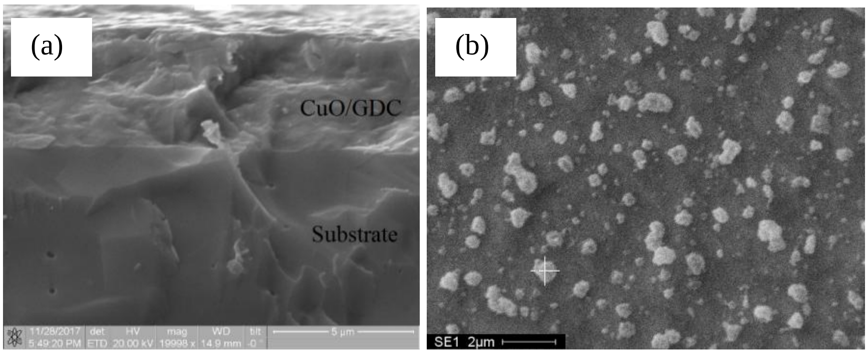

Fig. 1. The cross-section SEM image (a) of as-deposited CuO/GDC film on 10Sc1CeSZ substrate. Surface of Cu/GDC film after reduction in hydrogen at 600°C (b).

In order to prevent this process, the influence of pre-annealing of the as-deposited films in air atmosphere in the temperature range 1000–1200°C was studied. X-ray diffraction showed that after annealing at 1000°C, the film is saturated with oxygen and Cu_2O phase is transformed into CuO. It is shown that pre-annealing at a temperature of 1000°C does not prevent the agglomeration of Cu in a reducing atmosphere. As we have shown, the pre-annealing at 1200°C, which is successfully used for nickel-containing films, also cannot be used for magnetron sputtered copper-based films due to Cu evaporation. Thus, the problem of Cu agglomeration after heating in a hydrogen atmosphere still remained unresolved.

The catalytic activity of the magnetron sputtered Cu/GDC films will be determined at the next stage of research.

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HYBRID DC+HIPIMS MAGNETRON SPUTTERING DEPOSITION OF CU AND CUO FILMS*

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Direct current (DC) magnetron sputtering is the most basic and inexpensive type of magnetron sputtering. But during DC magnetron sputtering the plasma concentration is low (about 10^9 cm^{-3}), and its ionic component is represented mainly by the ions of the working gas (Ar^+). In high-power impulse magnetron sputtering (HIPIMS) plasma density could be as high as 10^{12} cm^{-3}. However, a significant disadvantage of HIPIMS is the reduction in the films deposition rate compared to DC sputtering. Different ways have been offered to improve deposition rate, for example, pulse waveform modulation [1]. Another perspective approach is hybrid technology, known as hybrid DC + HIPIMS co-sputtering process [2].

The properties of Cu and CuO films deposited on glass and Si substrates in DC + HIPIMS mode of magnetron sputtering have been investigated. Hybrid mode (DC + HIPIMS) of the magnetron sputtering was realized at an average power of 0,5 kW, applied to a planar magnetron with a Cu target. The main parameters that changed during the experiments were: amplitude of pulsed discharge current, pulse frequency, average power of DC-discharge in hybrid mode DC + HIPIMS. In the latter case the total average discharge power and the duration of high-current pulses are remained unchanged - 500 W and 100 µs, respectively. The amplitude of the current pulses varied from 20 to 300 A, and the pulse repetition rate varied from 100 Hz to 500 Hz. Figure 1 shows the current-voltage characteristics of a magnetron discharge in various modes at an argon pressure of 0.3 Pa.

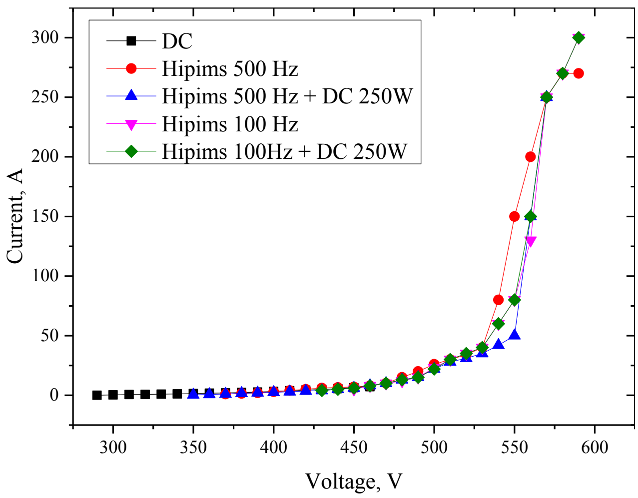

Fig. 1 Volt-ampere characteristics of a magnetron discharge in various modes at an argon pressure of 0.3 Pa.

Thin Cu films were obtained and their properties (resistivity, surface morphology, hardness) and the deposition rate were measured depending on the deposition regimes. It was established that the deposition rate in the hybrid mode (DC + HIPIMS almost coincides with the deposition rate in the DC mode (5.8 and 6 µm/hour, respectively) and more than twice the deposition rate in the HIPIMS mode (2.6 µm/hour) at the same average power (500W).

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INFLUENCE OF VACUUM-ARC AND MAGNETRON DISCHARGES COMBUSTION MODES ON STRUCTURE AND PHASE COMPOSITION OF THE FORMED COMPOSITE TIN-CU COATINGS*

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The paper studies the formation conditions, structure and phase composition of the TiN-Cu composite layers which received at different values of the arc current and the magnetron discharge current. The composite layers deposition was carried out in a modernized installation equipped a vacuum-arc evaporator and a planar magnetron [1]. Main plasma parameters generated at low-pressure vacuum-arc and magnetron discharges were studied with the help of a single Langmuir probe. It is shown how much the plasma concentration and the ion current density on the substrate changes depending on the change in the currents a magnetron discharge and vacuum arc evaporator. For example, at a constant pressure P =8*10^{-3} Torr with a discharge current of magnetron increase from 0.2 A to 0.6 A concentration of plasma grows from 2.6x10^{12}cm^{-3} to 1.1x10^{13}cm^{-3}.

Some results on the composite coatings TiN-Cu synthesis at different values of arc current and magnetron discharge current have been received. The layers' thickness was from 2-3 µm to 5-7 µm depending on the duration of the depositing time.

X-ray phase analysis is performed and according to this analysis the samples contained Ti_2N, TiN phases with different crystal cell and volume fraction. Besides the reflexes of copper with the intensity of about 1-2% there are fixed (Fig.1). With the help of a METAM PB-22 microscope the structure of a surface TiN and TiN-Cu coatings was investigated.

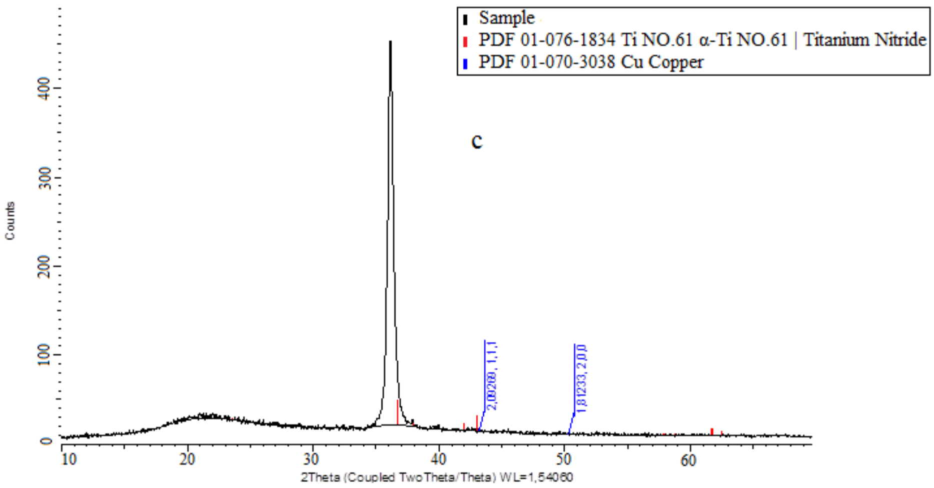

Fig. 1. XRD patterns for coating TiN-Cu (80A, 1,1A, 8x10^{-3} Torr)

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* The work was performed within the State task of Russian FARO (project No. 0336-2016-0005).

APPLICATION OF LOW-TEMPERATURE PLASMA

THE FORMATION OF A PLASMA ANODE IN A HIGH-CURRENT ELECTRON GUN WITH THE USE OF A HYBRID DISCHARGE

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The plasma anode is one of the key elements of high-current electron guns used to generate low-energy (up to 40 keV) beams, which are widely used for surface modification of materials [1, 2]. To improve the beam homogeneity, it is preferable to create a plasma anode with an increased ion concentration in the peripheral region. For this purpose, in [3], it was proposed to use a hybrid discharge that combines a high-current reflective (Penning) discharge (HCRD) with vacuum arcs initiated by a dielectric surface flashover.

In this work, we investigated the spatial structure of the glow and the temporal dynamics of such a discharge with an increased (relatively to [3]) anode voltage, and also carried out thermal imaging measurements of the energy density distribution over the beam section.

It was found that in the range of 0.1−1 mTorr, the time delay of the HCRD ignition does not exceed 15 μs and weakly depends on the working gas (argon) pressure and depends somewhat more on the amplitude of the voltage pulse applied to the anode (Fig. 1). In the range of anode voltages of 6−10 kV, the voltage and current discharge waveforms are very stable, as well as the ignition of vacuum arcs. Vacuum arcs provide a luminescence structure like a ring (Fig. 2), which makes it possible to improve the homogeneity of the energy density distribution over the beam cross section.

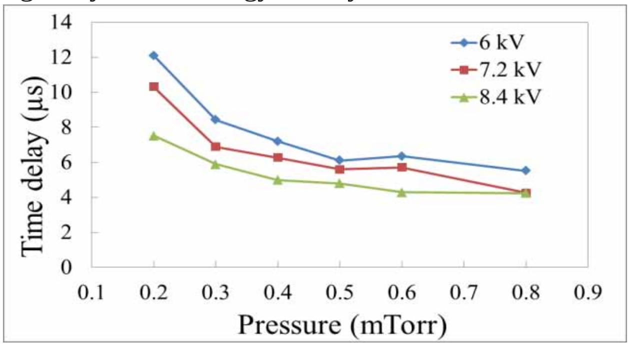

Fig. 1. Dependence of the time delay of the ignition HCRD on the argon pressure at different values of the anode voltage amplitude.

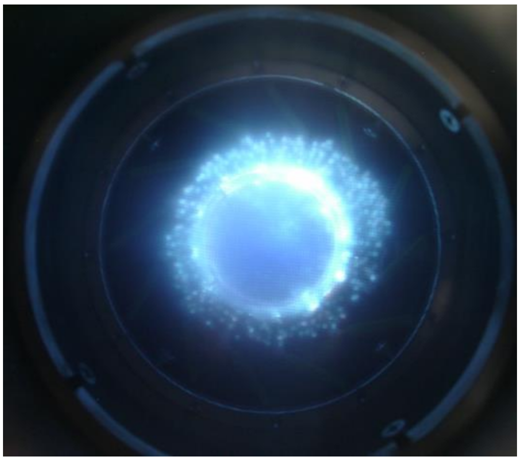

Fig. 2. The time-integrated glow of the discharge plasma. Anode voltage − 7.2 kV, argon pressure − 0.5 mTorr.

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MODELING OF THE SYNTHESIS OF ‘CORE-SHELL’ COMPOSITE PARTICLES BASED ON SEGREGATED OXIDATION OF TITANIUM AND SILICON TETRACHLORIDES IN FLOW-TYPE PLASMACHEMICAL REACTOR*

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Synthesis of nanocomposite powders of oxide ceramics is one of the most promising trends in up-to-date technologies. These powders belong to new class materials with controlled physico-chemical properties ranged depending on their applications. In particular, nanosized titania (TiO2) powders are being widely used in industry. In many applications it is required to extremely inhibit photocatalitic activity of TiO2 nanoparticles. For instance, it is the case when TiO2 pigments are used to modify physico-chemical properties of paint films, plastic materials, in paper manufacturing as well as that of sun blocking agents. In order to achieve this it is necessary to decrease an area of photo-active free surface of titania pigment as much as possible, with titania optical properties being unchanged. This requirement might be met by the synthesis of nanocomposite ‘TiO2 core - SiO2 shell’ particles. In these powders the greater thickness of silica amorphous layer and the lesser its microporosity, the lower photoactivity of the composite powder [1]. In numerical study [2] first time the simulation of one-step synthesis of composite TiO2/SiO2 nanoparticles in the working zone of plasmachemical reactor has been performed providing segregated oxidation of titanium and silicon tetrachlorides. The range of varying the flow rate of mixture of air and silicon tetrachloride allowed a decrease of reacting flow temperatures below 1200 K at which a formation of chlorosiloxanes (SiOxCly)n is possible. In addition, in the model a minimal shell thickness is not restricted.

In this work the results of simulation of aforementioned one-step synthesis of composite TiO2/SiO2 nanoparticles have been presented taking into consideration above mentioned aspects.

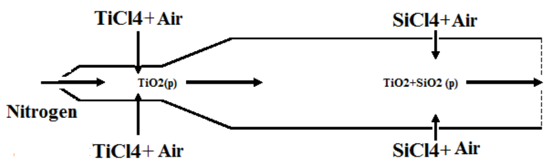

Fig. 1. Diagram of the working zone of the flow-type reactor. N_2 mass flow rate – 1 g/s. Mass average temperature of nitrogen plasma jet – 4500 K. Air+$TiCl_4$ mixture flow rate – 2.5 g/s, air+$SiCl_4$ mixture flow rate – 1.0 g/s. The model accounts for a synthesis of TiO_2 vapors, followed by formation and growth of titania particles as result of coagulation process.

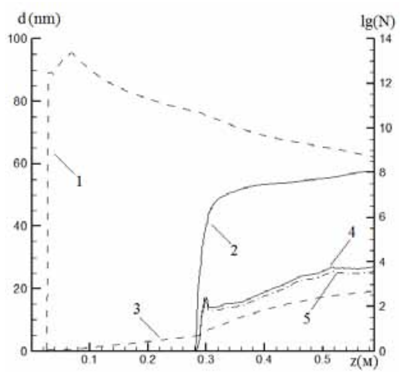

Fig. 2. Mass average particle diameter (nm) and logarithm of the particle total number distributions along the reactor: 1 – logarithm of the total number of TiO_2 particles; 2 – logarithm of the total number of composite particles; 3 – diameter of TiO_2 particles; 4 – diameter of composite particles; 5 – diameter of TiO_2 core of composite particles.

The results of the numerical investigation show that 50% of particles at the reactor exit are TiO2/SiO2 composite ones. The shell thickness is approximately equal to 1.5 nm.

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STUDY OF OZONE PRODUCTION IN A DIELECTRIC BARRIER DISCHARGE IN OXYGEN-CONTAINING MIXTURES FOR PLASMA ASSISTED COMBUSTION

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Active studies of plasma assisted ignition and combustion are currently under way [1, 2], because low-temperature non-equilibrium plasma is an effective tool for accelerating chemical processes associated with combustion. A dielectric barrier discharge (DBD) is of particular interest for combustion applications due to relative simplicity of its technical implementation and the ability to be easily integrated into various gas ow configurations [3].

The paper presents the results of experiments on the generation of ozone by a barrier discharge in oxygen and in a mixture of oxygen and methane, as well as the results of numerical simulation. For various experimental configurations, the dependences of [O_3] on the electric power deposited in the discharge are obtained. In addition, the work presents the results of experiments on the combustion of fuel-air mixtures of different degrees of enrichment.

The simulation of the barrier discharge is performed by simulating a sequence of discharge pulses with a given repetition rate. Analysis of the simulation results showed that the main mechanism leading to a decrease in the ozone concentration when methane is added to oxygen is the dissociation of methane in the discharge, which leads to the formation of hydrogen atoms, triggering the chain mechanism of ozone destruction.

The simulation results are in qualitative agreement with experimental data.

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THE STUDY ON PULSED ELECTRON BEAM ENERGY DISSIPATION IN GAS COMPOSITIONS OF INCREASED PRESSURE IN THE PRESENCE OF A CONDENSED PHASE (WATER, ASH)*

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The urgency of the project is justified by serious environmental problems of the environment (cleaning of flue gases) both in Russia and abroad. Electronic continuous accelerators (Indianapolis, USA and Karlsruhe, Germany) are currently used to purify flue gases. The initiation of plasma-chemical processes by a pulsed electron beam is one of the actively developing methods of activating chemical processes. The use of pulsed electron beams ensures the formation of plasma with a high degree of nonequilibrium in the ion and electron temperatures, which causes a number of advantageous features of this process when used in various industrial processes. The transfer of industrial processes to a new level of energy and resource efficiency is a modern trend with scientific and economic validity. Reduction of unproductive energy losses for heating nodes, aggregates, binders by combining reaction and plasma volumes will lead to higher productivity and economic efficiency of production. The use of nonequilibrium, fast-flowing processes in plasma will significantly increase the speed of chemical processes, and, therefore, reduce costs.

However, one of the important factors restraining the development of flue gas cleaning with the use of pulsed electron accelerators is the lack of an adequate physical model based on experimental data of the processes occurring during the interaction of pulsed electron beams, not only with model objects in the condensed and gas phase, but also with objects with a complex chemical composition, which are basic in technological processes. The complexity of the development of physical models is complicated by the nonlinear nature of the processes of energy absorption carried by beams, the formation of charged and excited particles, chemical reactions in the interaction zone, secondary radiation, and a number of other phenomena accompanying the interaction of pulsed energy flows with matter in the condensed and gas phases. A significant role in solving this problem is assigned to experimental research, experimental data both from the point of view of providing results for the formation of a model and its testing, and from the point of view of a quantitative description of the processes accompanying the development of specific technological processes.

In this work, the process of energy dissipation of a pulsed electron beam in gas compositions in the presence of a condensed phase will be investigated. The main components of flue gases (N_2, CO_2, O_2) were chosen as gas compositions. Water, ash were chosen as a condensed phase. These substances are either components of flue gases, or initial reagents or products of plasma-chemical reactions of the purification process using pulsed electron beams.

The TEA-500 accelerator and a drift volume were used in studies of the process of propagation of pulsed electron beams in gas compositions of increased pressure in the presence of a condensed phase (water, ash). The help of reverse current shunts, the reverse current and the current of the electron beam reaching the end flange of the drift tube determined.

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ELECTROSPARK METHOD OF OBTAINING NANOPOWDERS*

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The development of energy-saving, environmentally-friendly methods for obtaining nanopowders of various substances is an urgent issue of modern science. This is due both to the practical need for the creation of nanomaterials, which are widely used nowadays due to their uniqueness, and the fundamental need to understand the processes that occur in the preparation and application of nanoparticles by various methods [1-2].

In work the electrospark method is used to synthesize metallic nanocomposite. The following components were included: an electrode system; movement system; system for measuring processing parameters (oscillograph and current sensor, high voltage voltage divider, manovacuum meter); source of current pulses; vacuum system (vacuum pump, gas cylinders with working gas, gas routes, gas cranes). The peculiarities of the installation are the application of the power supply circuit from two generators, working on one interelectrode gap. The generator consists of three main units: low-voltage part, high-voltage part, control system. The high-voltage part of the generator is designed to form the initial spark channel. The low-voltage part of the generator serves to transfer the energy of the capacitor to the spark channel. The generator control system is designed to synchronize the high-voltage and lowvoltage parts of the generator. The main parameters of the generator: a) high-voltage part: pulse duration 1 μs, pulse amplitude 18 kV, pulse energy 0.01 J; b) low-voltage part: duration of low-voltage pulse 5..100 μs, stored energy 0.1..0.6 J, frequency 0.1..5 Hz.

The essence of the electric spark method of obtaining nanoparticles is as follows: a metal plate (copper, zinc, iron), which is an electrode, will be located in the chamber. After the preliminary pumping, the gas cuvette is filled with gas (argon, nitrogen, air), depending on the type of compounds synthesized. At the end of this, the pulse generator is started, simultaneously with it the system of movement of the metal plate automatically turns on. The process of nanoparticle production begins. At the end of this process, the generator switches off automatically, and the movement system returns to the starting point. The method for obtaining nanoparticles is based on the use of the energy of an electric spark discharge, formed between the electrode and the target. When a voltage pulse is applied between the electrode and the target surface, a plasma channel of a spark breakdown is formed with an initial diameter RK ~ 0.1 mm. The current flowing through the channel heats it, the pressure in the channel rises, the channel expands. The plasma temperature reaches values of $3.8\cdot10^4$ °K, the energy flux density in this case is 10^6-10^9 J/m^2. As a result of the action of a concentrated energy flux on the target, a rapid local overheating of the surface leads to sublimation of the material. Under the influence of gas dynamic forces, the target material is removed from the discharge region where the nanopowder is condensed and formed, and due to the special design of the electrode system, the formed nanopowder is deposited in a special trap. As a result, the resulting nanopowder will obtain a composition identical to that of the target, or an oxide corresponding to the material of the electrode. Sedlating materials will be used as targets for the research: steel (st3), copper, zinc. The use of an electrode tool with an erosion coefficient smaller than that of the target will allow synthesizing a nanomaterial that has the chemical composition of both electrodes used. The energy in the plasma channel is sufficient for the plasmochemical process to proceed, as a result of which it is possible to form composite nanomaterials with a solid solution. An additional regulator of the properties of synthesized nanoparticles can be the composition of the gas phase used in the production process. The properties of the resulting nanomaterials evaluated by IR analysis, transmission electron microscopy, X-ray dif-fraction analysis, BET surface area analysis, TG/DSC/DTA thermoanalysis.

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TEMPORAL CHANGES OF THE IR SPECTRA OF HEAVY WATER AFTER ITS TREATMENT BY DIFFUSE DISCHARGE AND AFTER IRRADIATION BY A NANOSECOND DURATION STREAM OF ELECTRONS*

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Investigations of the absorption spectra of heavy water treated by a diffuse discharge preionized by fast electrons with a short rise-time of voltage pulse and after irradiation by a nanosecond duration stream of electrons are presented in this report. With repeated irradiation of water, a change in the absorption spectrum of the substance was recorded. Analysis of the absorption spectra of water in the IR range showed the difference between the absorption spectra of irradiated and non-irradiated water and the change in the spectrum after irradiation over time.

* The work is performed in the framework of the State task for HCEI SB RAS, project #9.5.2.

ATMOSPHERIC PRESSURE DIFFUSE DISCHARGE TREATMENT OF AQUEOUS SOLUTION OF METHYLENUM COERULEUM*

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Recently, various methods of degradation [1] of different type of organic pollutants in waste gas and water have been studied. One of the possible way for water treatment is direct UV-photolysis, as well as in combination with a variety of chemically active species (O, H, OH, H_2O_2) [2]. In [3] was shown, that methanol concentration in water-methanol solution decreased 23 times under the action of UV-radiation with wavelength of 222 nm and presence of nitric acid. However, in a coloured wastewater, UV-light cannot penetrate deep into the water. Thus the decolourization is the most significant problem for the methods based on UV-photolysis. Since high voltage discharges generated in ambient air above the solution surface produce various oxidative species, they may be utilized to degrade organic dye molecules. In this study, we used runaway electrons preionized diffuse discharge (REP DD) where the tip high voltage electrode was placed above the surface of aqueous solution of *methylenum coeruleum* poured into a quartz cuvette. The cuvette was set up on the grounded plane electrode, the distance between the solution surface and the cathode was 8 mm. REP DD was formed by NPG-18 3500N generator produced negative voltage pulses with amplitude up to 18 kV in an incident wave and pulse repetition rate of 100 Hz.

Figure 1 shows the transmittance spectra of aqueous solution of *methylenum coeruleum* before and after REP DD plasma treatment during 10 and 20 minutes. As can be seen, the transmittance changed a lot in the visible spectral range after 20 minutes of exposure, but still remained significant in the UV range. It reveals that products of chemical reaction between oxidized and dye-molecules are smaller fragments of dye-molecules, and it takes longer time to completely destroy them into inorganics compounds.

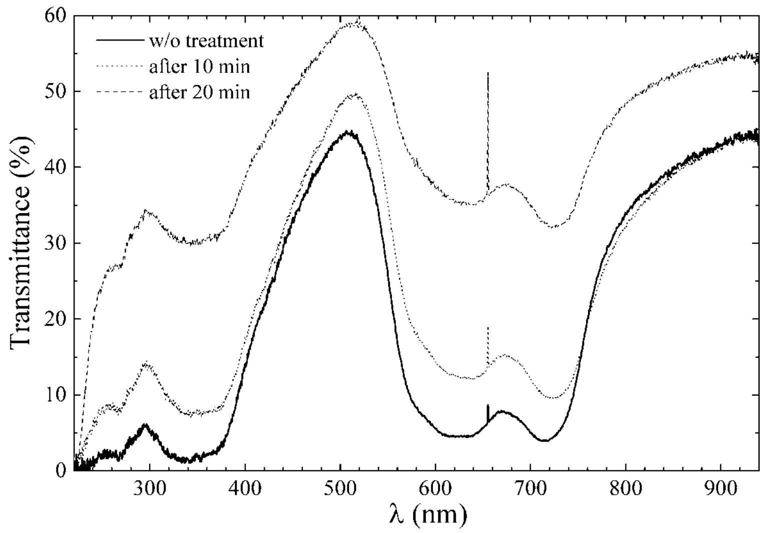

Fig. 1. UV-transmission spectra of aqueous solution of *methylenum coeruleum* before and after diffuse discharge treatment during 10 and 20 minutes.

Thus, experiments have shown that REP DD plasma treatment in ambient air may be used for decolorization of wastewater. Utilizing this method in combination with photo-dissociation process may be a promising wastewater treating technology in the textile industry.

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LASER-PLASMA SYNTHESIS OF DIAMOND FILMS*

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The operation of a setup based on a previously created microwave module [1, 2] and the newly developed quasi-cylindrical cavity in the TM_{012}–mode is considered (Fig. 1). Unlike the traditionally used scheme of cylindrical cavity for microwave plasmatrons, when the cavity is divided by a quartz partition into a working chamber where plasma is formed and a microwave input chamber to prevent breakdown with higher gas pressure, our solution in the form of a quasi-cylinder allows laser beam input. A laser beam injected through an evanescent waveguide passes through a not very dense microwave plasma, forming a spot of near-surface laser plasma at the plasmatron output. The microwave module allows one to initiate microwave plasma synchronously with laser radiation pulses (1-5 µs, 30-150 kHz) with an adjustable phase (delay) and provides a basic background, reducing the ignition threshold and increasing the spot area of the laser plasma. Preliminary experiments have shown the operation of the microwave cavity and a possibility of synthesizing a diamond-like film on a molybdenum substrate (Fig. 2).

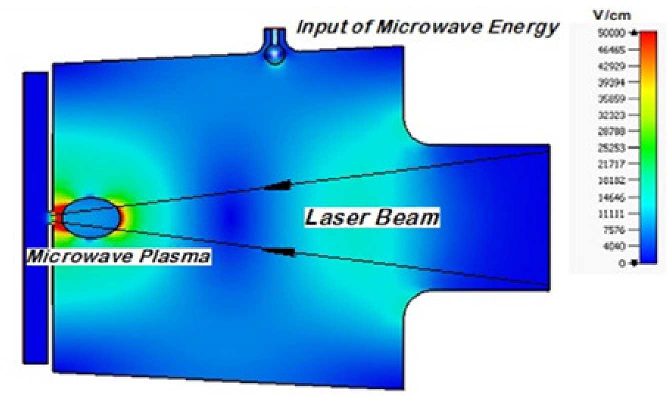

Fig. 1. Calculation of electric field configuration in a quasi-cylindrical cavity, TM_{012}–mode, copper, f = 2.47GHz, P = 5 kW. Plasma simulation - graphite, σ =10^{-4} См/м, ε = 12, Emax= 75 кV/cm.

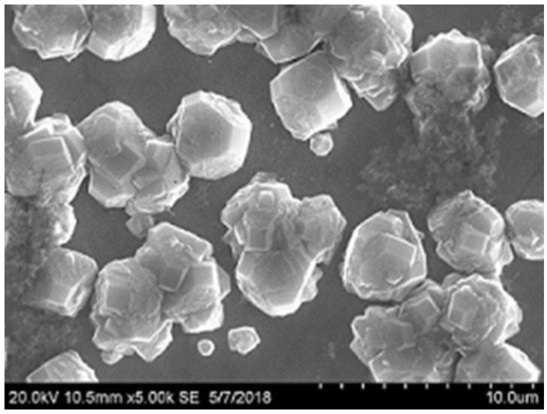

Fig. 2. Results of synthesis of a diamond-like film on a molybdenum substrate in an atmosphere of gases: CH_4, H_2, Ar.

The results of experiments on the interaction of microwave plasma with a CO_2 laser beam will be presented. Experimental estimates of the effect of microwave plasma on the ignition thresholds, the surface spot configuration, and the bulk torch of laser plasma will be given.

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EFFECTS AFFECTING THE MORPHOLOGY OF MICROSPHERES OBTAINED IN THERMAL PLASMA FLOW*

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A technique of the introduction of spherical particles, solid and hollow, in the matrix of constructional materials and coatings is being rapidly developed both in applications and science [1]. Nano- and micro-scale hollow particles, in which gas distributes in the volume or concentrates in separate inclusions, can be synthesized by treating both precursors [2] and different types of powders having the developed bulk structure [3]. Heating due to melting of the condensed phase up to the formation of hollow particles is observed in both cases.

In our theoretical and experimental studies we used silicon dioxide (SiO_2) obtained from sifted silica sand at Tuganskoe deposit due to its high SiO_2 concentration (98 ÷ 99.2 wt.%). Sifted silica sand also contained such impurities as refractory oxides Al_2O_3, Fe_2O_3, CaO, MgO and TiO_2 in the amount of much less than 1%. The experimental plasma generator was used to treat the powder agglomeration based on sifted silica sand [4].

Figure 1 presents a photograph of the plasma treatment of the powder agglomeration at stationary operation conditions. Plasma treatment parameters included 250 A current, 110 V voltage, 0.4 g/s and 1.1 g/s flow rates respectively for carrier gas and plasma gas, and 2.2 kg/h powder discharge.

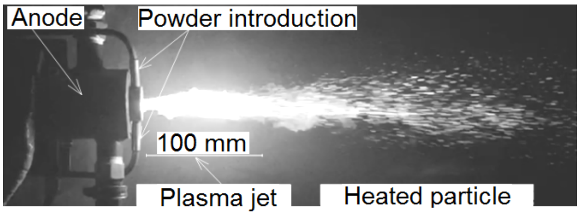

Fig. 1. Photograph of powder agglomeration plasma treatment.

Figure 2 presents scanning electron microscopy (SEM) observations of the individual powder particle and obtained microspheres. According to this figure, the agglomerated particle represents a coalescence of heterodisperse particles. The shape of the agglomerated particle is considered to be oval.

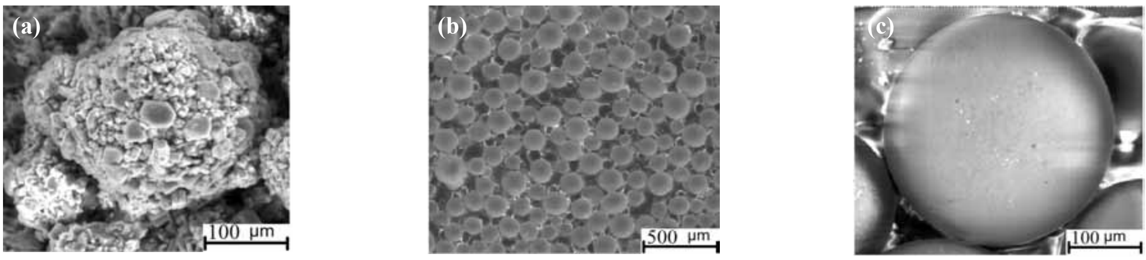

Fig. 2. SEM images of agglomerated particles: *a* – powder; *b, c* – microspheres.

The first important point is that the outer diameter of initial particles approaches to that of obtained hollow microspheres. This fact is supported by SEM images presented in Figure 2. As can be seen, the size of particles before and after the plasma treatment is almost similar. Micron-sized additional particles form on the surface of the hollow particles due to the disintegration of agglomerates during their travel in the dusty plasma flow.

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PHYSICAL AND TECHNICAL PROCESSES OF OBTAINING SILICATE MELTS AND MATERIALS BASED ON THEM IN LOW-TEMPERATURE PLASMA*

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Currently, it is not possible to obtain a silicate melt homogeneous in temperature and composition from raw materials with a melting point of more than 1500 °C using traditional technologies. The use of energy of low-temperature plasma makes it possible to increase the heating rate of silicate mixtures hundreds of times and to achieve consistently high temperatures of 3000–3500 °C upon receipt of silicate melts from raw materials with a melting point of 1500 °C and more. The development of methods for producing silicate melts using low-temperature plasma energy is of current interest.

Based on the results of theoretical calculations and the established modes of heat transfer when melting silicate raw materials using low-temperature plasma energy, the individual advantages of electroplasma installations were previously established in comparison with the silicate materials traditionally used in the processing of silicate materials. Based on the analysis of melting furnace designs, traditionally used in the preparation of silicate melts, years of experience in optimizing the parameters and design of plasma-chemical reactors, plasma variants for the production of chemically homogeneous silicate melts are proposed.

It was established experimentally that the operating conditions of an electroplasma installation make it possible to achieve specific heat fluxes of $1.0–2.6 \cdot 10^6$ W/m^2, sufficient to produce a melt with the required temperature and viscosity.

As a result of the analysis of the work of the created plasma installations, taking into account their features and shortcomings, an experimental plasma-chemical reactor (RF Patent 2503628) was developed to produce silicate melts (Figure 1).

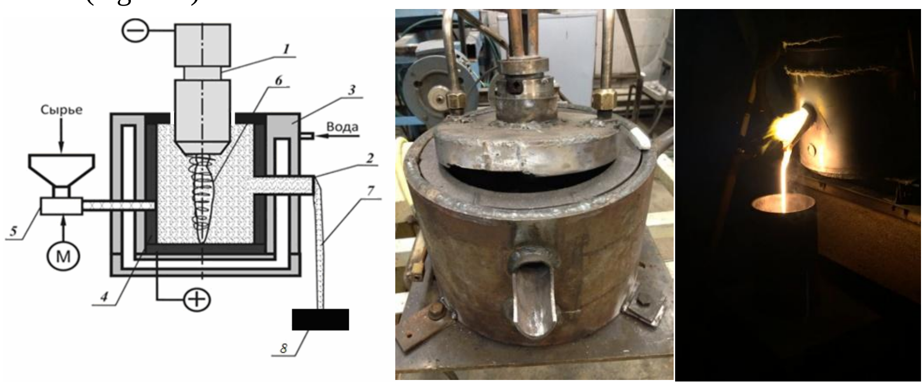

Fig. 1. Diagram of an experimental plasma setup for producing high-temperature silicate melts: 1 - plasma torch; 2 - drainage chute; 3 - water cooled melting furnace; 4 - graphite crucible; 5 - screw feeder; 6 - plasma arc; 7 - silicate melt; 8 - device for collecting the melt

Production of silicate melts in low-temperature plasma conditions proceeds in two stages: simultaneous melting of all phases of the mixture with the formation of a heterogeneous melt and homogenization of the melt under conditions of low viscosity due to overheating of the material above the melting temperature, in contrast to the melt production according to the traditional technology consisting of four stages: the formation of eutectic melts, the dissolution of the refractory components in eutectic melts, the production of a heterogeneous melt and its homogenization.

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STUDY OF SOME OPTICAL PROPERTIES OF TIO THIN FILMS PREPARED BY ION SPUTTERING

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The knowledge of optical properties of materials in IR range is important for different optoelectronic devices such as bolometers, transition edge sensors, etc. The optical and thermal properties of thin films are different from bulk materials [1]. Metal and metal oxides films are under consideration for the optoelectronic devices sensitive elements [2].

Titanium oxide (TiO) thin films (with a thickness of 500…600 nm) were prepared with ion (current I = 100…150 mA, voltage U=400…500 V) sputtering in a mixed argon and oxygen medium (pressure P = 2…3 mPa). Layered silicate plates were used as substrates. Samples were characterized by FTIR (FSM 2201 spectrometer), XRR (with the procedure [3]) and laser profilometry. The films were identified as cubic titanium monoxide. The spectral (within the wavelength range of 1.8…8.0 μm) transmittance T_λ and the optical density D_λ (defined as D_λ=-ln(T_λ)) of the films and the substrate are present in Fig. 1. The deposited films reduced T_λ values in 3…9 times.

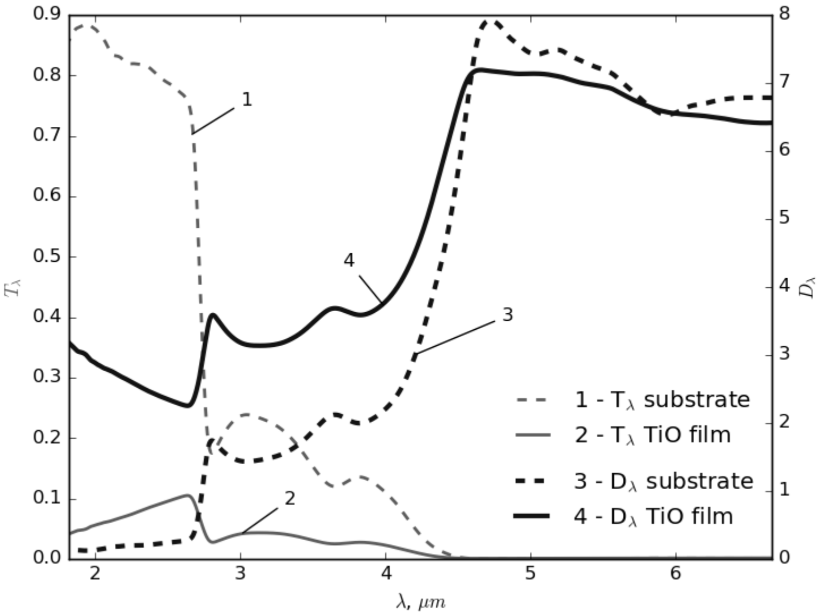

Fig. 1. Spectral transmittance T_λ and optical density D_λ

Cubic TiO films on silica are under consideration for manufacturing of systems with a low level of IR transmission. These samples are prospective for IR absorbers and detectors.

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EFFECTS OF DIELECTRIC BARRIER DISCHARGE GENERATED PLASMA ON THE PHYSICOCHEMICAL AND TECHNOLOGICAL PROPERTIES OF GEOMATERIALS*

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The feature of the mining and metallurgy development in Russia is the increase in volume of rebellious natural raw materials (geomaterials), with low content of valuable components and finely disseminated aggregates composed of minerals with similar process properties [1]. To date in Russia and other world countries the nontraditional (nonmechanical) processes for physicochemical, electrochemical, and pulsed energy effects have been intensively advanced with intent to improve disintegration and opening of finely dispersed mineral aggregates, to enhance the contrast of structural-chemical and flotation properties of rebellious mineral materials [1-3]. In recent years, dielectric barrier discharge (DBD), as a common approach to generate non-thermal plasma at atmospheric pressure, has been proved to improve the physical and chemical properties (namely, hydrophobicity and hydrophilicity surface) of polymers and other materials.

This work presents new experimental data on changes in the structural and chemical surface properties, water contact angle, microhardness and floatability of semiconducting sulfide minerals and quartz as a result of low-temperature plasmas action produced by dielectric barrier discharge at atmospheric pressure under standard air conditions. The gas (air) temperature in the discharge region of the DBD cell (reactor) remained near room temperature for 30-60 s and generally increased with increasing applied voltage amplitude in the range of 2–20 kV and driving frequency in the range of 2–20 kHz. We examined the variations of DBD properties with changing applied voltage and frequency. The rational condition we defined here as the operational conditions of voltage and repetition driving frequency under which the highest changes of minerals properties are achieved (20 kV, 16 kHz, 8 µs voltage pulses, 100 ns pulse leading edge).

We performed our studies using samples of dry-crushed, pulverized and sieved to obtain a particle size in the range –100+38 µm sulfide minerals (pyrite, arsenopyrite, sphalerite) and polished specimens 1×1×0.45 cm in size. Microhardness of minerals in the initial state and after DBD-plasma treatment of polished specimens estimated by Vickers' method (HV, MPa) at microhardness-meter PMT-3M; indenter load 50 – 100 g for sulfide minerals, and 200 g for quartz, loading time 10-15 s. The change in the hydrophilic-hydrophobic state of the quartz surface was evaluated by the change in the water contact angle (Θ°) of the polished specimens surface by the sessile drop method using a microscope with the digital camera Moticam 2300 and the software suite Motic Image Plus 2.0 ML for image input and processing. The change in the flotation activity of minerals was measured by the recovery of sulfide mineral particles (pyrite, arsenopyrite, sphalerite) into the flotation froth. We examined the morphology of the minerals surface by analytical scanning electron microscopy (SEM–EDX) and confocal laser scanning microscopy (Keyence VK-9700).

Microstructural changes in the surface layer of minerals caused by DBD-plasma treatment resulted in an effective softening of their surface: the maximum relative change (decrease) in microhardness of quartz was observed after a $t_{\text{treat}} \sim 150$ s treatment and was 7% (from 1420 to 1321 MPa). Short plasma treatment of quartz ($t_{\text{treat}} = 10-30$ s) caused an increase in the hydrophobicity of the mineral surface: the contact angle of the quartz surface increased from 43.7° to 53°. With an increase in the treatment time ($t_{\text{treat}} = 30-150$ s) of mineral, there was a slight change in the contact angle from $44-47$° to 48.4° in quartz. In selective flotation of pyrite, arsenopyrite, and sphalerite, the optimal parameters were found of the preliminary DBD-plasma treatment ($t_{\text{treat}} = 30-50$ s) and the reagent regime has been optimized for sphalerite recovery, resulting in a 6% (from 45 to 51%) higher recovery of sphalerite, 4% lower recovery of arsenopyrite (from 11 to 7%), and 22% lower recovery of pyrite (from 37 to 15%).

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MATCHING OF MASS SPECTRA OF IONS AND TERAHERTZ RADIATION OF LOW-INDUCTIVE VACUUM SPARK WITH LASER INITIATION

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One possible source of broadband THz radiation (TR) can be a vacuum spark with laser initiation. It is possible to propose several mechanisms for generating THz radiation from a vacuum spark differing in their origin: thermal (Planck) radiation, radiation of electrons in a magnetic field of a discharge current (cyclotron mechanism), and radiation caused by rapidly developing instabilities arising in the micropinch structure [1].

The goal of this work was to study the mass spectra of ions emitted from a plasma of a laser-initiated vacuum spark, and to compare the charge distribution of ions with the intensity of TR generated by the plasma.

The magnitude of the energy of the initiating discharge laser pulse $E_L \leq 20$ mJ with duration $\tau \leq 20$ ns. The laser radiation was focused on the anode of the discharge system. The energy released in the discharge is $E_D \approx 17$ J at voltage on the discharge capacitance U_{AK} =12.5 kV. Electronic plasma temperature $Te \leq 1$ keV.

In this work a time-of-flight mass spectrometer with a magnetic analyzer was used [2]. In the experiment, the mass spectra of plasma ions of a vacuum spark and the intensity of a terahertz signal were simultaneously recorded.

Figure 1 shows for comparison of two types mass spectra obtained for the mode with stable TR detection (amplitude at the detector P_T = 500 mV) and signal at the noise level (amplitude P = 50 mV). When results were processing, the concentration of electrons was calculated by the formula

$$N_e = \sum Z \cdot N_i(Z), \qquad (1)$$

where N_i (Z) – number of ions with charge Z.

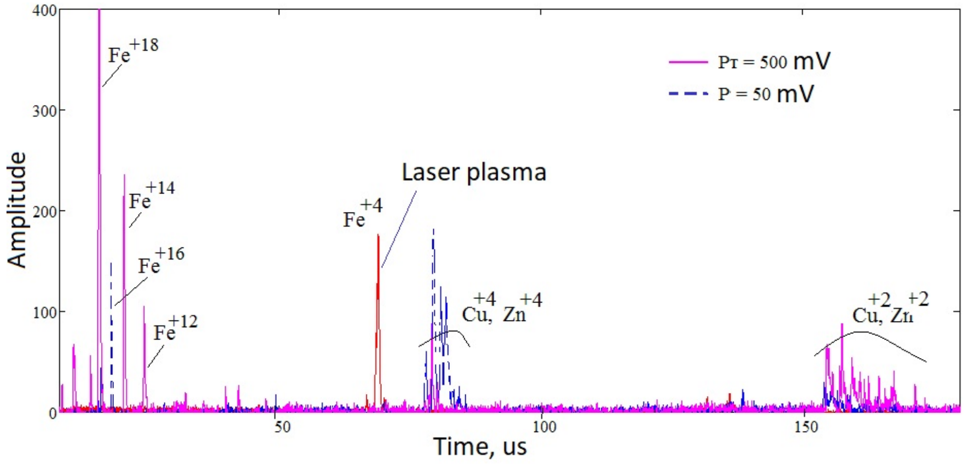

Fig.1. The averaged mass spectra at a fixed current of the magnetic analyzer: 1) continuous lines - the amplitude of the terahertz signal P_T = 500 mV; 2) the dotted line - the amplitude of the signal at the noise level is P = 50 mV.

The analysis of mass spectra showed that, generation of TR has threshold nature, non-linearly dependent on the concentration of Ne. From estimatimation of the electron concentration for modes with $P_T \approx 500$ mV and $P \approx 50$ mV, we can assume a power-law dependence of the intensity of terahertz radiation $P_T \sim (Ne)^{x,}$ where x ≥2.

Apparently, the condition for "effective" generating TR in the plasma vacuum spark is existing of high electron density in plasma in the presence of certain configured manner sufficiently strong magnetic fields.

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INTERACTION OF LOW TEMPERATURE PLASMA WITH FUSION MATERIALS

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The paper presents research results of candidate and structural materials of a fusion reactor. In order to support Tokamak KTM as well as to create a base for interaction between plasma of fusion reactor and materials, established a simulation tests-bench with plasma-beam installation [1].

The installation provides the following plasma current parameters: diameter of plasma flux to a target is up to 30 mm; maximum magnetic field strength generated at the chamber axis of plasma-beam charge is 0.1 Tl; intensity of current in plasma is up to 1A; plasma flux density in a beam is up to 10^{22} $m^{-2}{\cdot}s^{-1}$; ion concentration in plasma is up to 10^{18} m^{-3}; electron temperature of plasma is up to 100 eV; ion energy is up to 2 keV.

The simulation test-bench with plasma-beam installation, which is line simulator, was involved into tests to study how low temperature plasma affect plasma, beryllium and tungsten. A plasma-beam charge was implemented on such working gases as helium, hydrogen and deuterium.

To research structures, determine samples' element composition and their physical and mechanical properties as well as to study fracture mode of irradiated layers of materials, such methods as X-ray diffraction phase analysis, transmission electron microscopy, scanning electron microscopy, and emission spectroscopy were used, in addition micro hardness of material surface was defined after plasma effect.

Based on result of research, initial data on interaction of plasma with material surface, which are actual for applying in fusion reactor, have been obtained. In the course of works data on parameters of plasma-beam charge in different gases was received, installation was systematically upgraded to make plasma specification of simulation test-bench more similar to plasma of fusion reactor.

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OPTIMIZATION OF THE NUMERICAL MODEL OF THE TRIGGERABLE LTD SPARK GAP SWITCH

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In LTD generators, one of the main parts of the primary discharge circuit is the triggerable spark gap switch. For the cavities with oil insulation, the OrCAD switch model was developed [1-3] by taken into account the effect of the trigger pulse on the triggering time of these switches and it's spread. According to the real design, the switch in this model is simulated as a block consisting of six independent spark gaps connected in series. However, because of such detailed description of the switch structure this initial model is quite complex causing significant complications in simulation of the full generator in case it includes numerous switches. To avoid that complexity, in the given paper we investigate the possibility to optimize the initial complex model, and present at the output much less complicated switch model with acceptable simulation error.

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STUDY OF ADHESION CHARACTERISTICS OF A NI-CU SURFACE ALLOY FORMED BY A LOW-ENERGY HIGH-CURRENT ELECTRON BEAM

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Ever since the treatment of material surfaces by deposition of functional metallic coatings and thin films has become a widely used, the adhesion of these coatings to substrates represents a scientifically interesting topic with a huge practical impact in industry. Adhesion is one of the most important characteristics of coating efficiency. As structural factors (such as the state of the substrate surface, substrate roughness, the thermal expansion coefficients, etc.), and factors associated with the deposition process (such as internal stresses, thickness and the presence of impurities and structural defects in the coating, etc.) affect the adhesion of the coating to the substrate. The influence of some factors can be avoided by using various methods of preparing the substrate surface, others using additional interlayers of materials that help reduce the internal stress of the coatings. However, in all these cases, the level of adhesion will be the result of the interaction of two surfaces at the interface - the surface of the coating and the surface of the substrate. The [1,2] report that the forming surface alloys method using by a low-energy high-current electron beam (LEHCEB) can drastically improve the adhesion of the coating to the substrate. The surface alloy is formed by alternating operations of deposited a film on a substrate, followed by LEHCEB liquid-phase mixing of the film with a substrate. This method of coating synthesizing leads to the formation of a transition layer between the coating and the substrate, in other words to the blurring of the interface between the coating and the substrate. Figure 1 shows an example of such a transition layer, which can be several microns thick.

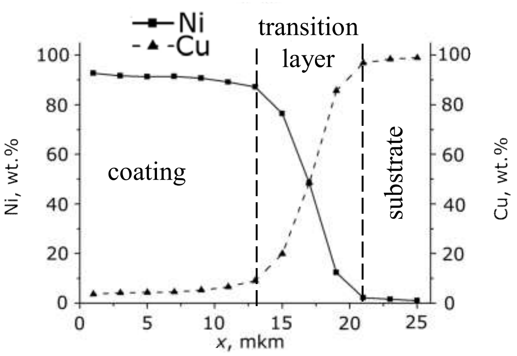

Fig. 1. In-depth elements distribution in Ni-Cu surface alloy.

However, there is practically no information in the literature on the effect of this transition layer on the adhesive characteristics of surface alloy. Therefore the aim of this work was to investigate the effect of thickness of the transition surface alloy layer on its adhesive characteristics.

The electron-beam machine "RITM-SP" with an explosive-emission cathode and a plasma-filled diode generating the LEHCEB was employed in the work [3]. This machine is equipped with a magnetron sputtering system enabling formation of surface alloys. The adhesive characteristics of the surface alloy were investigated for the Ni-film/Cu-substrate system. This system of materials is a good model system for studying the adhesive characteristics of the surface alloy, because copper and nickel form a continuous series of solid solutions that is important for the formation of a transition layer. In addition, nickel is a harder material than copper, which means that the system as a whole (both the coating and the substrate) will work under loads. Different transition layer thickness was obtained by varying the parameters during the formation of the surface alloy, such as different thickness of the deposited film and the parameters of the LEHCEB (energy density, number of pulses). Different techniques like SEM, XRD, EDS have been used for characterization of the surface morphology, phase and elemental composition of the surface alloys. Much attention in the work has been paid to investigation of in-depth elements distribution of surface alloy and adhesion characteristics by scratch-test.

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OBTAINING NANODISPERSED PRODUCT OF TITANIUM DIBORIDE IN AN ARC DISCHARGE OF MAGNETOPLASMA ACCELERATOR

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Titanium Diboride (TiB_2) is a promising material for using it in many industrial applications. TiB_2 has combination of thermal, mechanical and electrical properties such as high thermal conductivity, extreme melting point, high hardness, elastic modulus and fracture toughness, good electrical conductivity, chemical stability and excellent wear resistance [1-5]. These outstanding properties can be used in different engineering applications, such as impact-resistant armour, cathodes in Hall-Heroult cells, solar thermal absorbers and cutting tools [6-8].

Nowadays there are a lot of ways to synthesize TiB_2: in situ, sol-gel reduction, mechanical alloying, gas phase method, carbon/boron thermal reduction method, self-propagating high-temperature synthesis, chemical vapor deposition [1, 6, 9-11]. However, there are some problems in synthesize nano-dispersed powders TiB_2: obtaining unsatisfactory size and dispersal of the product, high time and energy costs.

In this paper, a new method of synthesis is proposed – plasma dynamic synthesis in a hypersonic plasma jet using titanium electrodes. The installation called a coaxial magnetoplasma accelerator (CMPA). The main part of it consists of a coaxial electrode, a central electrode, isolators and a plasma formation zone.

In order to initiate an arc discharge it is necessary to put an amorphous boron powder into a plasma formation zone and stretch between coaxial and central electrode conductors. Different ways of initiation an arc gas discharge can be suggested for obtaining TiB_2 powdered products using titanium conductors, carbon fibers or graphite aerosol (graphitization). Depending on the method of initiation of the arc discharge, a different output of titanium diboride is obtained. The higher the content of titanium diboride in the product, the better and higher will be the properties of the ceramics obtained on the basis of the powder. The content of TiB_2 in the experiment using Ti-conductors is 26,8 %, using carbon fibers is 62,1 % and with graphitization is 93,2 %. All experiments were implemented with the argon atmosphere, which filled the volume of the reactor chamber. The time of the process of initiation an arc discharge is various and depending on the using conductors: with Ti-conductors t = 110 ms, with carbon fibers t = 150 ms, graphitization t = 160 ms. The faster the process of exploding the conductors, the less boron powder warmed up and interacted further with titanium eroded from the surface of the electrode of the trunk. So in the experiment with graphitization the highest yield of TiB_2 is 93,2 %.

Based on the obtained powder, ceramics was synthesized by the method of spark plasma sintering. This method is one of the perspective method due to the speed of the process (5 min), high temperature (1800 ˚C) and pressure (60 MPa). Obtained ceramics showed high value of hardness. The values of the obtained hardness were: 1) Ti-conductors P = 24,7 GPa; 2) Carbon fibers P = 28,3 GPa; 3) Graphitization P = 30,3 GPa. The higher the content of the TiB_2 the harder the ceramic samples.

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OPTICAL CHARACTERISTICS OF LITHIUM FLUORIDE CRYSTALS IRRADIATED BY LITHIUM IONS AND MICROWAVE DISCHARGE PLASMA*

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The paper presents the results of studies of the optical characteristics of LiF crystals after irradiation with a beam of lithium ions, with a fluence of about 10^{17} ions / cm^2 and an energy of 100 keV. The absorption spectra of lithium fluoride crystals exposed are some overlapping bands with absorption maxima at 250 nm, 441 nm and 500 nm. The first and second bands are responsible for the absorption of F and F_2 ($F_3{}^+$) color centers, respectively. The third is the plasmon band resulting from the formation of lithium nanoparticles from implanted ions. The luminescence spectra of lithium fluoride crystals when excited by laser radiation with a wavelength of 470 nm showed that, along with the luminescence band with peaks at 550 and 680 nm, a luminescence band with a maximum at 650 nm was detected. The first and second bands are characteristic of the luminescence of the $F_3{}^+$ and F_2 color centers, respectively, which appear in the thin surface layer upon irradiation with ions. The third band resulted from lithium colloids. Measurements of the kinetic characteristics of the luminescence revealed four decay times, namely 15.3 and 7.6 ns, close to the characteristic decay times for the F_2 and $F_3{}^+$ centers of the luminescence in the LiF crystal. In addition, two fast components with a decay time of about 2.3 and 0.5 ns were found that were associated with the luminescence of lithium nanoparticles.

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FEATURES OF SELF-SUSTAINED MAGNETRON SPUTTERING OF EVAPORATING METAL TARGET

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Studies of the mechanisms and regularities of the discharge operation were performed when the magnetron sputtering system (MSS) was operating in the self-sputtering mode of an evaporating metal target under conditions of extremely low pressure in the vacuum chamber (less than 0.1 Pa) due to the termination of the inlet of the sputtering gas argon. It has been established that the magnetron is able to work in gasless mode if, due to evaporation of the target, the concentration of metal atoms near the surface of the target is necessary to maintain the discharge. Using the example of an MSS with a copper target, the minimum required power has been determined, starting from which the discharge can function without the inlet of the sputtering gas. The threshold power value depends on the crucible substance and the type of power source (mid-frequency, high-current). Thus, in the case of using a copper target in a molybdenum crucible and a mid-frequency power source, the minimum power density required for stable self-sputtering without supplying the sputtering gas is 19.4 W/cm^2, and in the case of a high-current power source - 33 W/cm^2. It has been revealed that thermo-electronic emission is not a necessary factor in maintaining the discharge of a magnetron operating on vapor of a target substance.

It has been found that the erosion yields of metal targets at evaporation reach several tens of atoms per ion, which is an order of magnitude higher than the sputtering yields. Due to this, the coatings deposition under self-sputtering conditions takes place without reducing a deposition rate as compared to the case with sputtering gas.

The evolution of the intensity of the spectral lines of the plasma optical radiation during the transition of a magnetron with an evaporating copper target into the self-sputtering mode and switching off the sputtering gas was studied. A correlation was found between the intensity of the spectral lines of copper atoms and ions with the evolution of evaporation. As the intensity of evaporation increases, argon atoms are displaced from the burning region of the discharge in front of the target.

The flux densities of deposited particles and energy under conditions of intense evaporation of a copper target were studied. It was found that in the considered MSS power range, due to evaporation, the flux density of the deposited particles increases by about an order of magnitude. The main source of energy entering the substrate is heat radiation from the target. The magnitude of the total energy flux is about the same as when the target is sputtered in an argon atmosphere, and in the self-sputtering mode.

Experiments were carried out on the deposition of copper coatings with argon at a pressure of 0.2 Pa and in the full self-sputtering mode at a pressure of 0.01 Pa. Different power sources were used (mid-frequency and high-current). The microstructure, crystal structure and roughness of coatings obtained at different evaporation rates were studied. It turned out that under conditions of intensive evaporation, there is no noticeable pronounced influence of the self-sputtering factor and the type of power source on the studied characteristics of copper coatings. At low evaporation rates, the structural characteristics of the coatings turn out to be better in the gasless mode.

This work was supported by the Russian Foundation for Basic Research (Project No. 18-08-00454)

OBTAINING OF HIGH-POWER ELECTRON BEAMS IN A PLASMA ANODE ELECTRON SOURCE POWERED BY MARX GENERATOR WITH MATCHED LOADS *

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The paper presents the results of experiments for obtaining high-power microsecond electron beams of circular and rectangular cross-section in an electron source with an explosive emission cathode and a plasma anode. The use of the plasma anode allows to increase the current and energy of the electron beam, increases the reliability of the electron source operation, provides the possibility to realize a controlled mode of the source operation with the beam current control without changing the accelerating voltage.

The source of high voltage was the Marx generator with stages in the form of artificial long lines with matched loads. The generator consists of 6 stages and has air isolation. The wave impedance of the generator is 25 Ω, the pulse duration at half-height equals to 5 μs and corresponds to the time of the wave travel along the line. The generator provides obtaining rectangular voltage pulses up to 200-250 kV without reflections at a constant arbitrary resistive load in a single-pulse mode. In the case of time-varying resistive load, the wave form of the generated pulses differs from the rectangular one, but the pulse duration remains the same [1, 2].

In the experiments, round and rectangular multipoint cathodes with round and rectangular regions of location of the points, respectively, were used. To form a plasma anode, plasma was injected into the interelectrode gap using plasma guns with a discharge along the dielectric surface. Beam formation was realized when the longitudinal magnetic field was applied to the interelectrode gap, plasma anode, and the transportation region.

The performed experiments show that the use of a generator with matched loads prevents the breakdown and ignition of the arc discharge in the interelectrode gap. It is possible to implement operation modes of the electron source with quasi-constant values of the accelerating voltage and beam current. At the accelerating voltage of 200 kV, electron beams of round or rectangular cross-section of ~100-200 cm^2 with a current of 1-1.5 kA and duration of 5 μs were received. The rotation of the beam around the axis was registered. The possibility to extract an electron beam through a foil window into the atmosphere was tested.

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PRODUCTION OF AL-O-N NANOPOWDERS IN A PLASMA REACTOR WITH A LIMITED JET FLOW*

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Experimental studies of aluminum oxynitride nanopowders synthesis in a reactor with a confined plasma jet by the interaction of disperse aluminum with ammonia and oxygen in the flow of nitrogen plasma generated in an electric arc plasma torch are carried out.

Optimal design of the reaction prechamber of the reactor selection were made.

Powders with an average particle size in the range of 20-200 nm, having a cubic structure and consisting of aluminum oxynitride phases, were obtained.

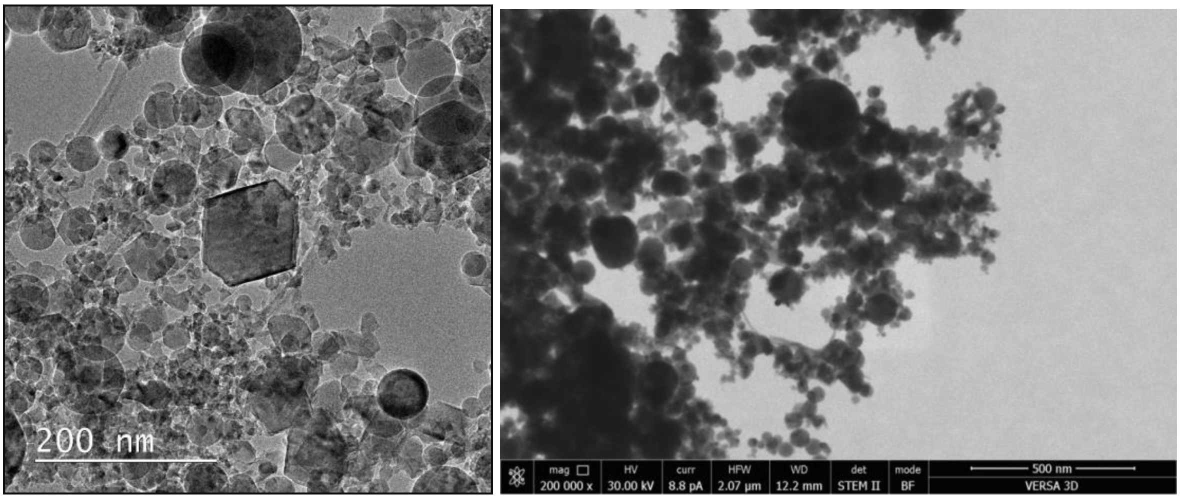

Fig. 1. SEM and TEM images of obtained nanopowders.

As a result of the research, the possibility of controlling the phase com-position of the obtained nanopowders, as well as such properties as the specific surface area and the content of nitrogen and oxygen in the product, has been established

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OBTAINING THE ULTRADISPERSE MATERIAL OF THE Al-Mg-O SYSTEM BY PLASMA DYNAMIC METHOD

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Nanomaterials, in particular metal oxides, have a wide range of applications. Prospects for use of such materials are associated with their unique features in the ultrafine state. Aluminum oxide is a wide-gap dielectric with high wear resistance, mechanical and chemical resistance, which is used in medicine, optics and various technical fields [1, 2]. It is known that there is a possibility of improving the characteristics and improving the functional properties of the material due to the introduction of a small amount of the $MgAl_2O_4$ spinel phase into its composition [3].

To date, there are many methods for producing nanosized aluminum oxide, for example, gas-phase method, electric explosion method of conductors, or sol-gel method [4-6]. Of course, these methods have advantages and disadvantages. The disadvantages include unsatisfactory dispersion of the product and high duration and multi-stage nature of the material production process.

The method of plasma dynamic synthesis developed at the Tomsk Polytechnic University is devoid of the above-noted drawbacks and can be considered as an alternative method for producing nano-dispersed aluminum oxide. This method is based on the use of high-current high-voltage coaxial magnetoplasma accelerator of the erosion type with an aluminum accelerator channel. The main advantage of the method is its speed – the synthesis time takes less than 1 ms [7]. At the same time, the resulting products are distinguished by their high dispersion. The simplicity of the method lies in the fact that, using a simple aluminum alloy tube containing about 7% magnesium as a barrel, and when the gaseous precursor oxygen is pumped into the reactor chamber, it is possible to obtain unique aluminum oxide and spinel phases. Synthesis of aluminum oxide was carried out due to erosion of the aluminum barrel. When the arc flows through the acceleration channel, the base material, aluminum, is produced, after which it is carried into the chamber, where it enters into a plasma-chemical reaction with oxygen, forming the desired product. To obtain purer product of plasma dynamic synthesis, it was proposed to use a system with the separation of the synthesized product into a large and small fraction.

The paper shows experimentally the possibility of producing aluminum oxide and spinel in a system based on the use of a pulsed high-current coaxial magnetoplasma accelerator of the erosion type. The average particle size in the product varies from 50 nm to 250 nm. It should be noted that the installation allows you to change the ratio of Al_2O_3 to $MgAl_2O_4$. In the future we plan to use this material to obtain bulk ceramic samples.

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ANALYSIS OF ELECTRICAL CHARACTERISTICS OF CERAMICS ON THE BASIS OF ZnO-Bi_2O_3, OBTAINED BY SPARK PLASMA SINTERING*

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Ceramic zinc oxide varistors are the most promising fast-acting means of protecting electrical circuits from impulse overvoltages. They have high non-linearity of electrical characteristics. Due to the recent need to protect semiconductor control circuits of power equipment, the limiting voltage of which only slightly exceeds the operating one, it is important to increase the nonlinearity of varistors in the field of switching currents, limiting overvoltage to a safe level [1].

Obtaining ceramic samples from nanopowders is a challenge. Currently, effective methods of pressing powdered materials include the following methods: hot pressing, hot isostatic pressing and spark plasma sintering (SPS). The main advantage of the SPS is the speed of the process of consolidation of powders [2]. The paper considers the possibility of sintering powdered materials of the ZnO-Bi_2O_3 system, obtained by the method of plasma dynamic synthesis (PDS) [2, 3] and under commercial conditions. The PDS method does not require preliminary preparation of the main precursors - zinc and oxygen. Zinc enters the plasma due to the electroerosive wear of the zinc barrel and is carried into the reactor chamber, which is pre-filled with oxygen. In addition, the channel of formation of the plasma structure can be filled with additional precursors (for example, bismuth), which also enter the plasma structure when initiating the arc discharge. Metallic bismuth Bi (purity 99%) in the form of a powder with an average particle size of about 100 microns was inserted into the channel of formation of the plasma structure of a high-current discharge at the beginning of the accelerating channel (AC) of the zinc barrel of a coaxial magnetoplasma accelerator (CMPA). During the course of the arc according to the AC, the production of the base material, zinc, which enters the plasma structure, in which bismuth is already present, occurs. After that, the plasma structure is carried into the chamber, where it enters into a plasma-chemical reaction with oxygen. The collection of the highly dispersed fraction of the product was carried out after its complete precipitation from the suspension on the walls of the reactor chamber. The sample was sintered using the IPA method in vacuum in a graphite mold under a pressure of 60 MPa and at a sintering temperature T = 1200 ºC.

The paper shows the possibility of obtaining ultrafine composite materials of the ZnO-Bi_2O_3 system with the core-shell structure using a high-current high-voltage coaxial magnetoplasma accelerator. In addition, studies have been conducted on the consolidation of materials by the method of spark plasma sintering. Sintered ceramics based on the PDS product is characterized by the fine-grained structure of zinc oxide ZnO (average grain size 1.3 μm) with a uniformly filled intergranular space bismuth oxide Bi_2O_3. Analysis of the current-voltage characteristics of ceramics of different composition showed a significant advantage (nonlinearity coefficient, breakdown voltage, leakage current) of using the PDS ZnO-Bi_2O_3 product with the core-shell structure compared to commercial materials.

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PRECISION CUTTING OF HIGH-TEMPERATURE DIELECTRICS BY THE FOREVACUUM PLASMA ELECTRON SOURCE*

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Electron-beam technologies find wide application for welding various kinds of materials [1], among which are cutting, welding, evaporation, surfacing. The interest in electron-beam processing of dielectrics has led to the development of forevacuum electron sources [2, 3], operating at pressures from a few to hundreds of pascals. The features of the operation of such sources, associated with the passage of electrons of the beam in a gaseous medium at elevated pressures, provide charge neutralization of the dielectric surface during processing. Due to this, forevacuum sources are capable of producing continuous electron-beam processing for a long time, and the beam power density achieved so far ensures effective precision cutting of such high-temperature dielectrics as ceramics and quartz.

This paper presents the results of usage the forevacuum source of a focused electron beam with currently record specific beam parameters (electron energy up to 30 keV, beam diameter up to 0.15 mm, beam power density in the crossover about 10^6 W/cm^2) [4, 5] for cutting of such dielectrics having high melting point as ceramic and quartz glass. The effect on the size of the single hole created in the dielectric of the main parameters of the electron beam processing mode (energy of electrons, beam power density and time of electron-beam processing) is investigated. It is shown, that depth of the singe hole created by the electron beam directly determined by the beam power density (fig 1), and for beam power density at the level of 10^6 W/cm^2 can reach several centimeters. Also the paper demonstrated the possibility of creating extended holes in ceramic and glass.

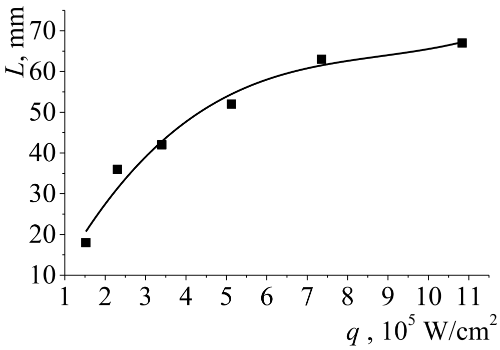

Fig. 1. The dependence of hole depth *L* on beam power density of the electron beam *q*

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DIRECT CURRENT ARC-PLASMA SYNTHESIS OF B-C POWDER PRODUCT*

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Boron carbide is widely spread, super-hard material, which is characterized by low density (~2.5 g/cm^3) high melting temperature (~2620–2740 °C), high resistivity to some radiation and other unique properties [1]. Boron carbide can be synthesized by several methods, such as: carbo-thermal reduction of boron oxide, plasma spraying, melt crystallization, and CVD [2-5]. Last years a new method of direct current arc discharge has been developed for carbon nanostructures [6] and boron carbide [7] synthesis. The main feature of this method is the possibility to operate at generating the ambient air plasma. This procedure is becoming possible due to carbon monoxide generation during arcing, that results in gas, which can insulate the reaction zone and prevent oxidation from synthesis products. The procedure implementation has been discussed before in [6-7]. In this paper we study the crystalline phase composition and crystallinity of powder products in link with a synthesis process time. The arc discharge experiments were conducted by DC APAS-method (direct current arc plasma air synthesis) at a plasma chemical reactor that is introduced in [7].

According to X-ray diffraction data (Shimadzu XRD 7000s, λ=1.54060 Å, CuKα) a typical product consists of three main crystalline phases: graphite (C (graphite)), boron oxide B_2O_3, as initial raw materials, and synthesized boron carbide $B_{13}C_2$. The phase composition depends on arc discharge tome as mentioned below in Fig. 1.

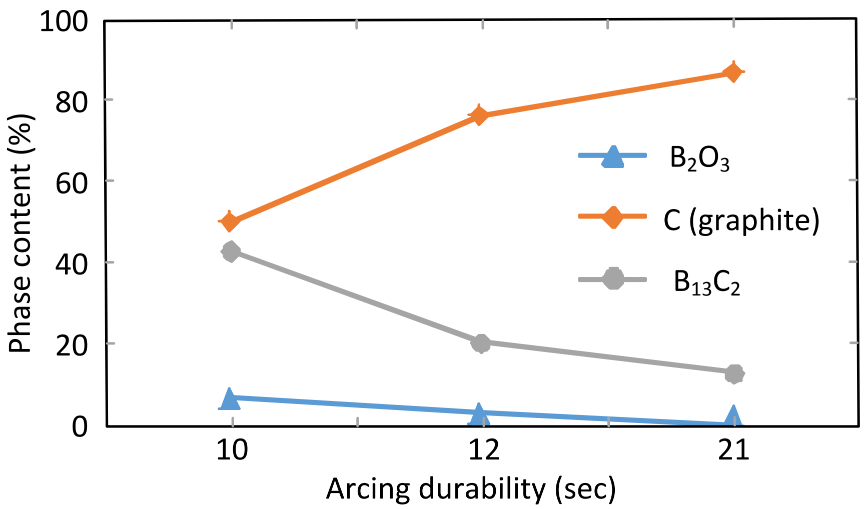

Fig. 1. Phase composition and arcing time dependence

The maximum time is 21 seconds that can lead to full mass of initial boron oxide consumption. At this time the content of graphite increases owing to the anode erosion effect [8]. According to these data we make a conclusion that arcing time influences the phase composition through energy input variation by time control. Besides, it is possible to obtain two phase composition of a product by full mass of the boron oxide consumption.

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PLASMACHEMICAL PROCESSING OF GERMANY-CONTAINING MINERAL AND TECHNOLOGICAL RAW MATERIALS *

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The aim of the work was to study the possibility of plasma-chemical enrichment of germanium-containing fly ash. The essence of the method consists in converting germanium in the form of monoxide into the gas phase and its subsequent separation from the solid phase.

Thermodynamic modeling of the Ge-O-C-N system showed (see fig. 1) That the minimum temperature for the existence of GeO is 900 ° C. Those. for a given composition of the mixture, monoxide below this temperature is unstable and, depending on the ratio of the components, passes into either Ge (at C> 15 g) or GeO2 (at C <15 g).

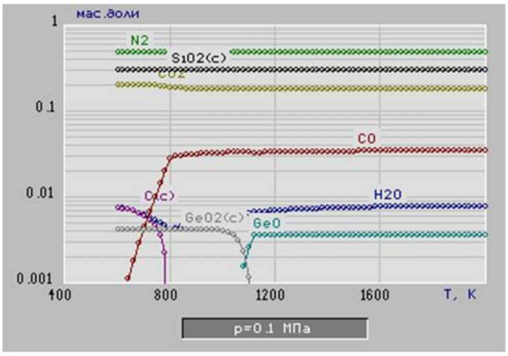

Fig 1. The equilibrium composition of the mixture: GeO2- 1 g, SiO2- 70 g, O2-35 g, N2-115 g, C = 15 g

In a direct-flow plasma-chemical reactor with hot walls, experiments were conducted to investigate the possibility of plasma-chemical extraction of germanium with the following parameters: air consumption – 2 g/s, consumption of germanium-containing ash from coal combustion - 1.5 g/s. The dependence of the degree of extraction of germanium in the gas phase on the composition of the plasma-forming gas was investigated. The composition of the gas phase in the reactor was changed by feeding propane.

As a result of processing raw materials, two types of solid products are obtained: molten slag and powdered ash. The residual germanium content in the slag was below the sensitivity limit (0.001%) of the method used. The powdery product of plasma chemical processing was characterized by a relatively low degree of extraction of ~ 70–80%, which is apparently explained by large particle sizes, which is why the necessary temperature was not reached. Considering the data obtained, as well as the fractional composition of the feedstock (particle size reached 5 mm), it was concluded that the processing of ash with the melting of its mineral part was expedient. This simplifies the processing scheme due to the simpler separation of gas from the melt of the mineral part of the ash.

Plasma-chemical processing of germanium-containing ash in a plasma-chemical reactor with a flowing melt film showed that the degree of germanium extraction from ash was 95-96%. The residual germanium content in the slag was 0.04% with the initial content of 0.65%. In the experiments, the supply of propane to the reactor was not used, and the residual germanium content in the slag approximately corresponded to the previous experiments in the direct-flow reactor without the supply of propane. Therefore, by optimizing the composition of the gas phase in the reactor, it is possible to further increase the degree of germanium extraction from the processed raw material.

Thus, the experiments carried out showed the possibility of efficient plasma-chemical separation of germanium from low-concentrated raw materials with the degree of enrichment in the resulting product up to 30-40 times.

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ENERGY DEPTH DISTRIBUTION OF PULSED ELECTRON BEAM OF WIDE ELECTRON KINETIC ENERGY SPECTRUM FOR AN ALUMINUM TARGET*

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An electron beam is a high-tech tool which can be used in various fields of radiation technology [1, 2]. Utilizing of pulsed electron accelerators with a wide range of electron kinetic energies significantly reduces the cost of their production. Besides, the electron beam ejected to the atmosphere can significantly expand its application scope. Transmission of the electron beam to the atmosphere trough sealing membranes substantially changes its initial spectrum. Therefore, knowledge of pulsed electron beam characteristics is necessary for use it for scientific and practice applications.

Current work analyze the pulsed electron beam extracted from the vacuum diode through a titanium foil (60 microns) of the diode exit window. Electron beam energy depth distribution was measured for a target made of different number of aluminum foils. A pulsed electron beam with a wide range of kinetic energies was generated by the ASTRA-M accelerator (260 kV of accelerating voltage, up to 1kA of beam current, 150 ns of beam pulse duration at FWHM)[3]. Total absorption calorimeter was used to measure beam characteristics. Calorimeter included two collectors: first for measuring of a beam energy after aluminum foils, and a second one for measuring total beam energy. All measurements were performed at 10^{-5} Torr background pressure after the exit window foil. As a result, the electron kinetic energy spectrum of the beam out of diode has been reconstructed. The calculation of electron energy spectrum after titanium foil was made with help of database[4].

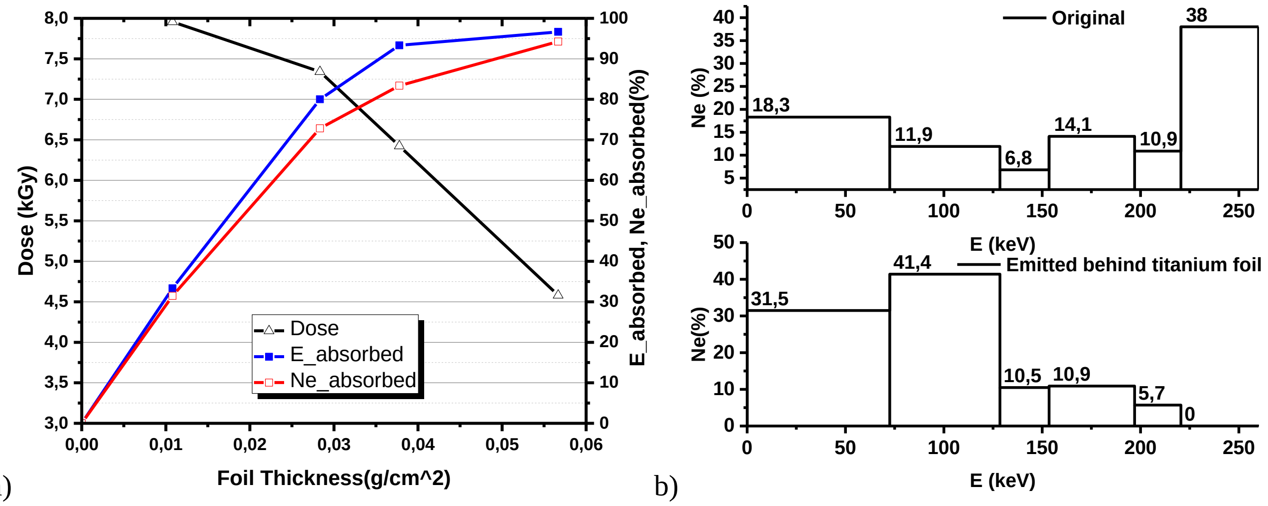

Fig. 1. a) Absorbed Dose, beam energy and electron numbers distribution from depth aluminum target, b) Electron beam energy spectrum before and after titanium foil.

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HARD ALLOY MODIFICATION BY GLOW DISCHARGE PLASMA

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The use of hard alloys makes it possible to process metals at ultrahigh cutting speeds since these alloys have a very high hardness and wear resistance. Such alloys are used in the processing of parts from high-strength, heat-resistant and stainless steels. Therefore, improving the performance characteristics of such alloys is an important task the solution of which will ensure an increase in labor productivity and economy of imported materials. One of the most promising is a method of improving the operational characteristics of cutting tools made from hard alloys by treatment with a glow discharge. A distinctive feature of this treatment is the versatility of the method with a high degree of productivity as well as the possibility to process much larger areas. Plasma treatment does not require the use of liquid solutions as a result it is environmentally friendly and energy-intensive.

The treatment of hard alloys was carried out by a dc glow discharge excited in a medium of residual atmospheric gases with a pressure of 1.33 ... 13.33 Pa at a voltage of 0.5 ... 5 kV, a current density of 0.05 ... 0.5 A/m^2, a pulse frequency of 35 KHz± 30 % and the ratio of the areas of the anode to the cathode 0.010 ... 0.015 [1]. Such processing ensures the formation of unique structural and phase states in their surface layers as well as a wide scale of structure modification [2, 3]. These changes lead to changes in the mechanical and operational properties of the surface layer.

The aim of this work is to study the effect of modifying treatment by a glow discharge on the structure and operational characteristics of hard alloys. Electron microscopic, X-ray diffraction methods were used for this study to analyze the phase composition, structure and properties of the surface layer. Along with the study of the structure, the hardness and wear resistance of the samples were studied. This study may determine how the structural changes in the surface layers affect the change in hardness and wear resistance of the samples. The measurement of the hardness of the samples was carried out according to the Vickers method. The study of the effect of treatment in a glow discharge on wear resistance was carried out on an equipment based on a machine for testing materials for friction and wear.

As a result of the research it was found that plasma treatment leads to an increase in the surface hardness of hard alloys by an average of 10 ... 15%. The processing of hard alloys with a glow discharge with certain technological characteristics leads to an increase in their wear resistance up to 3 times. Moreover, the modifying treatment leads to relatively uniform wear throughout the cutting until critical wear is achieved. The increase in hardness and wear resistance of the hard alloys is associated with the creation of a modified layer to a depth of 70 microns.

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ELECTRIC ARC SYNTHESIS OF MICRO DIAMONDS.*

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Currently, methods of chemical vapor deposition (CVD - chemical vapor deposition) or methods of self-organization at high pressures and temperatures are used to synthesize artificial diamonds. It was by these methods that large artificial diamonds and industrial-use diamonds were grown. In [1], it was reported about the effectiveness of the use of elements of the fourth group of the periodic table as catalysts in the process of diamond synthesis. The authors of [1] managed to grow diamond crystals with a size of 20–100 μm in 60 hours using the CVD method.

This paper presents the results of experiments on the synthesis of microdiamonds from graphite in an argon arc using germanium as a catalyst. To understand the synthesis of diamonds, one must have an idea of the temperature field in an arc discharge. The most reliable information about the temperature field was obtained by conducting a numerical experiment taking into account the greatest number of physical processes in [2]. The results of these studies allowed designing complex electrode assemblies both for the synthesis of nanotubes [3] and for the synthesis of diamonds in this work.

For this, a “hybrid” anode was made, consisting of a graphite frame with a diameter of 1.5 cm, into which a germanium rod 5 mm thick was inserted. Figure 1 on the left shows the traces left by diamond microparticles on the glass surface, and on the right - microdiamonds surrounded by germanium nanoparticles.


a)

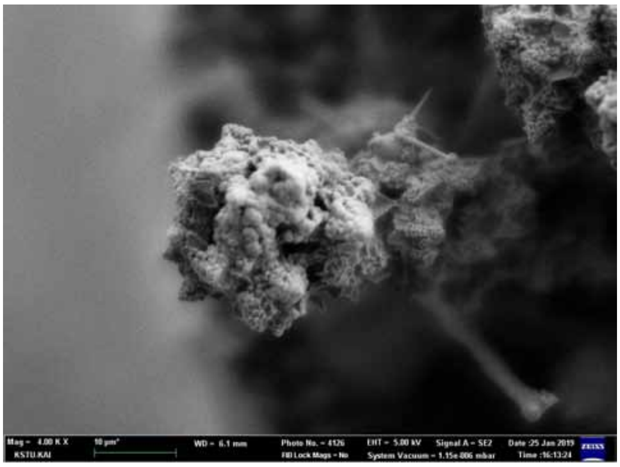
b)

Fig. 1. a) traces of microdiamonds left by their friction between the panes. b) micro-diamonds surrounded by germanium nanostructures. Magnification 4000 times.

It has been revealed that the forms of the grown nanomaterials are significantly affected by both the surrounding gaseous medium and the electrical parameters of the arc discharge — the current and the distribution of the electric field intensity. Simple microdiamonds were obtained, as well as diamonds of a complex configuration, which, apparently, were formed in this form due to the absence of an initial embryo. The formation of microdiamonds is a few tens of seconds, which is much different from the traditional methods of their production.

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PLASMA CHEMICAL PROCESSING OF HYDROCARBONS.*

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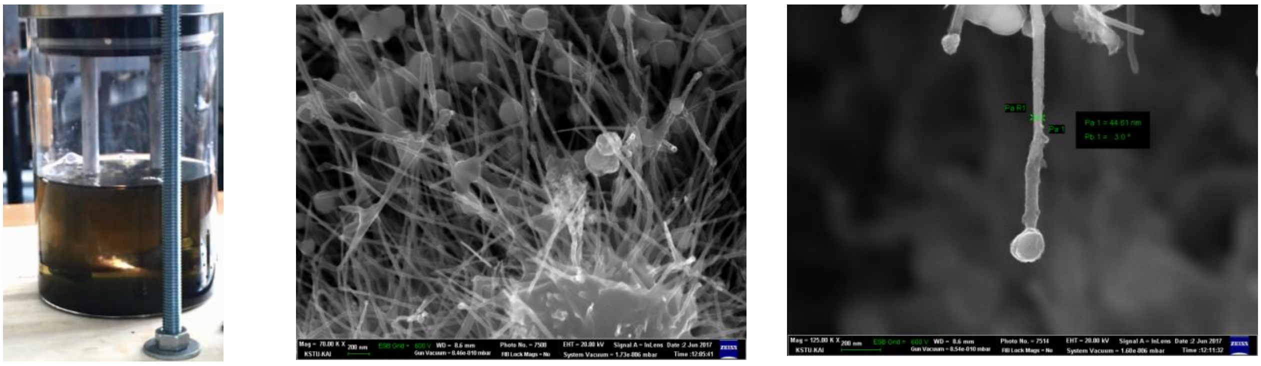
In the present work, a method of plasma-chemical processing of hydrocarbon raw materials with the aim of obtaining valuable products, including nanostructures, is proposed. For this purpose, a method of organizing an electrical discharge of direct current in the thickness of the liquid raw material was used. In order to automate ignition processes and optimize the discharge burning process, an installation with a rotating electrode mechanism was developed and designed, which eliminated sticking of the electrodes and discharge attenuation. In fig. 1 a) presents photograph of the discharge in the thickness of the hydrocarbon raw materials. The following operating modes were considered. When the distance between the electrodes is 0.5 mm, a stable arc is observed at currents of 0.1 - 1 A and at voltages of 550 - 100 V. With these discharge parameters, the decomposition of hydrocarbons into light fractions occurs. In the process of decomposition, the formation of a vapor-gas mixture is continuous, and the formation of carbon samples occurs in small quantities.

The products obtained as a result of the interaction of a gas-discharge plasma, initiated in the bulk of the hydrocarbon feedstock with the latter, were subjected to thorough analysis. In fig. 1 b) and c) images of carbon deposits formed at the cathode, taken with an electron microscope.

Nanostructures were formed in a chaotic manner in the form of closely woven threads. Since the nanotubes are twisted together, it can be assumed that they have a complex structure. In addition, multilayer nanotubes of the “Russian nesting doll” type were observed. A nanotube has a diameter of 44.04 nm, a nanotube similar to it, which is inside it, has a diameter of 18.46 nm.



a) b) c)

Fig. 1. a) Photograph of the arc discharge during the experiment with diesel fuel; Electron microscopic picture of carbon deposits at the anode: b) Increase of 70.000x., C) Increase of 125.000x.

The light and volatile fractions of oil produced during the plasma-chemical treatment of fuel oil were analyzed on a Chromatek Kristall 5000.2 chromatograph. Chromatographic analysis showed that the main products of the decomposition of hydrocarbons are: ethylene more than 40%, hydrogen 24%, methane 7%.

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PLASMADYNAMIC SYNTHESIS OF ULTRAFINE TITANIUM OXIDES

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Over the past decade, interest has increased in the creation of nanoscale materials due to their unique properties. One of such materials is titanium dioxide due to its characteristics, which is widely used in modern fields of science and technology, in particular, medicine, pigment production, microbiology, photocatalysis, etc. [1, 2]. Moreover, titanium dioxide is used in the coatings form serving to increase the mechanical strength, specific surface area and selectivity of catalysts obtained on their basis.

There are many different ways to produce nanosized titanium dioxide [3, 4], but they have several disadvantages: high cost of raw materials, multistage. This paper shows the synthesis of ultrafine titanium dioxide by the plasmodynamic method. The method allows to obtain material in a fraction of a second (10^{-3} sec.), is one-step and does not require any preliminary preparation, besides its implementation takes place in atmospheric conditions.

Plasmadynamic synthesis is realized in system, in which the main element is a pulsed high-current coaxial magnetoplasma accelerator (CMPA) of the erosion type with metal titanium electrodes. The power supply of the CMPA is provided from a partitioned capacitive energy storage with a capacity of up to C_{ch} = 28.8 mF and a charging voltage up to U_{ch} = 5 kV.

Figure 1 shows the SEM-image of the product obtained plasma-dynamic method. This study was conducted using a scanning electron microscope Hitachi TM-3000. The synthesized powder is sufficiently agglomerated, which is characteristic for electrophysical methods of dispersion [5]. Estimating the brightness and contrast of the image, we can conclude that the product consists of materials of similar density and is characterized by a fairly wide distribution in the range from 100 nm to 3 μm. There is the presence of single spherical objects with a size of 5 microns.

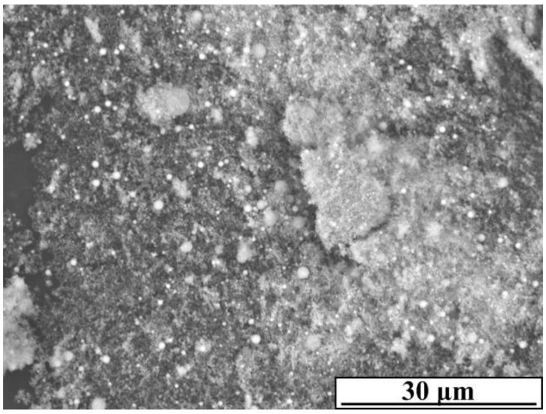

Fig. 1. The SEM-image of synthesize material

Powder of Ti-O phases were obtained by the synthesis in a supersonic plasma jet. The results of scanning electron microscopy have shown that the particles have a spherical form with their sizes varying from 100 nm to 5 microns.

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CONTROL OF THE PARTICLE SIZE DISTRIBUTION AND THE INVESTIGATION OF THE CRYSTAL STRUCTURE OF THE TITANIUM OXIDE POWDERS, OBTAINED BY PLASMADYNAMIC METHOD

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At the present time, titanium oxide (IV), such as TiO_2 (titanium dioxide) is widespread in many industries. It is used in the production of solid films in photocatalysis and solar energy; in addition, titanium dioxide has found its application in both chemical and pharmaceutical production [1-4].

An important problem is the development of methods for the direct synthesis of a finely dispersed phase, since it is possible to achieve improved characteristics of titanium dioxide only in a nanoscale form [5].

This paper shows a method for obtaining ultrafine powder by plasmodynamic synthesis. The main advantages of this method are the speed of the process (10^{-3} sec.), the absence of the need for preliminary preparation of the material and its constant dosing. Also, the method is environmentally friendly and safe.

The synthesize product without any preliminary preparation was investigated by x-ray diffractometry. The fig. 1 shows the diffraction pattern of the synthesized material and cards of the proposed phases. The analysis was performed using a Shumadzu XRD7000 X-ray diffractometer (CuK_α radiation) equipped with a counting monochromator. The full-profile analysis was carried out in the “PowderCell 2.4” software environment and the PDF4+ structural data base. Two crystal modifications of TiO_2 have been identified: anatase $aTiO_2$ with tetragonal syngony (no. 21-1272) and rutile $rTiO_2$ also with tetragonal syngony (no. 21-1276). There is a broadening of the peak in the range of 53.8 ÷ 54.5 degrees. However, its separation into 2 phases is clearly visible: $aTiO_2$ and $rTiO_2$.

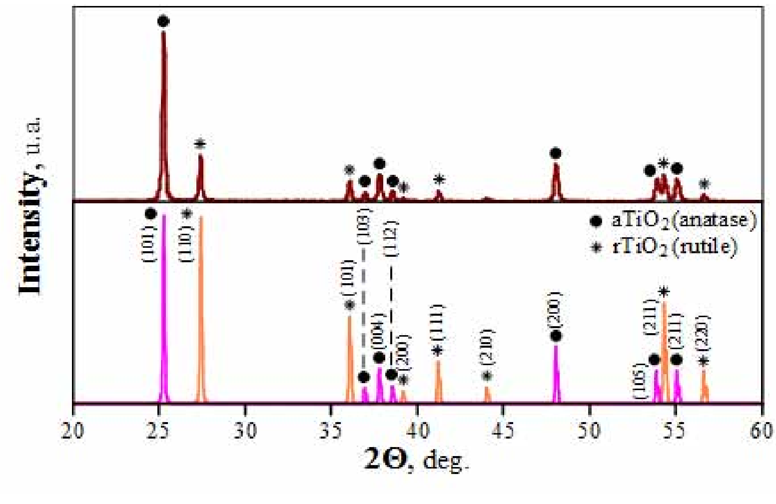

Fig. 1. Diffraction patterns of obtained material and proposed phases

The paper has shown the results about the synthesis of ultrafine titanium dioxide. X-ray phase analysis has determined the presence of 2 crystalline modifications of titanium dioxide: anatase with tetragonal syngony and rutile with the same syngony.

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CASCADE VOLUMETRIC ACCELERATION OF ELECTROHYDRODYNAMIC FLOWS*

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In this paper, we study the systems of electrohydrodynamic flows based on cascade acceleration [1, 2] - systems with ion injection into the acceleration unit (by corona or dielectric barrier discharge) and their further acceleration by synchronizing the movement of ions with the polarity of accelerating electrodes. To implement electrohydrodynamic flows cascade volumetric acceleration, the experimental setup was created (Fig. 1). It consists of two EHD cascade C_1, C_2 [3], Spellman SL2000 high-voltage power supply, plasma emitters (PE), current-limiting resistor R of 100 kΩ, high-voltage switch (HVS) that forms rectangular pulses [4]. HVS output voltage was smoothly regulated from 0 to 8 kV and monitored through a high-voltage probe with a multimeter V.

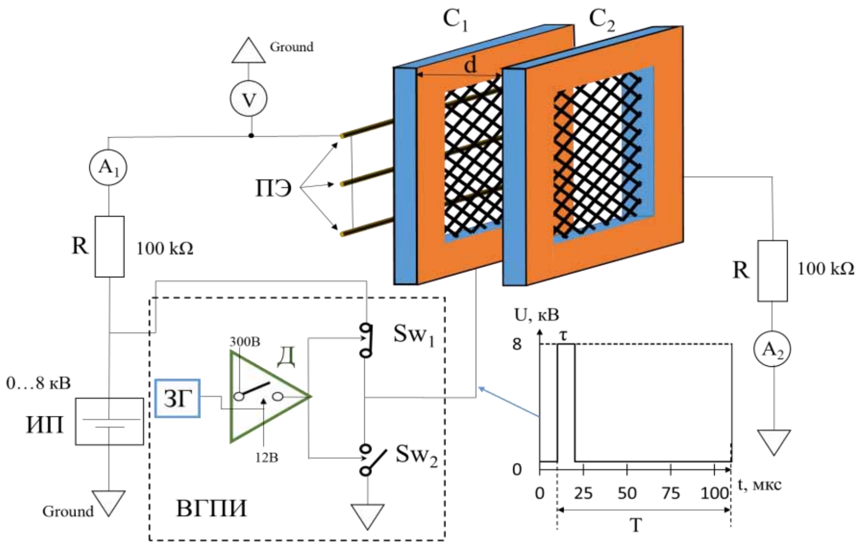

Fig. 1. Experimental setup to study the volumetric acceleration of EHD flows

The discharge current was measured by an A_1 microammeter, and output current by A_2. The number of emitters was selected on the basis of the range and sensitivity of A_1 and A_2 (10-100 μA). The impulse corona discharge was formed at the moment when control driver D open the switch Sw1 and close Sw2. Due to this, between the PE and first section grid high voltage difference is forming. The duty cycle of a rectangular signal and pulse repetition rate was regulated by the driving generator (DG). High-voltage switches Sw1, Sw2 are designed for operating at voltages over 10kV and consist of 8 modules of series-connected IGBT without snubber circuits, which reduces losses when working at high repetition frequencies and small pulse width (200 ns). According to the results of the study for a two-section accelerating module, an ion current at second section through A_2 can be achieved of up to 70% at a duty cycle of D = 0.1 and of 62% at D=0.5. Enhancement of the effectiveness of the EHD flows formation systems is important for creating aircraft [5, 6] on the base of these devices.

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SURFACE PROPERTIES OF POLYLACTIC ACID FILMS AFTER PLASMA TREATMENT

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Polylactic acid is a biodegradable, aliphatic polyester of lactic (2-hydroxypropionic) acid and widely used for medical purposes. Plasma modification of surface allows to change the surface properties (adhesion, wettability) of films and to sterilize the polymer films.

The aim of this work is the study of low temperature plasma influence on the polylactic acid films surface properties.

Materials and methods. The polylactic acid films were obtained by dissolving of polylactic acid PL10 (PURAC, Netherlands) in a solvent of trichloromethane (CHCl3) (EKOS-1, Russia). The resulting 1% solution in an amount of 10 g was poured into Petri dishes and left for 2-3 days. The films thickness was 20±0,1 μm. The plasma modification of polylactic acid films was done with using the experimental low temperature plasma device. The plasma treatment time of each film surface was 30, 60 and 90 seconds. The surface topography and the roughness of polylactic acid films were studied on atomic force microscopy (AFM) "Solver-HV".

Results. The polylactic acid films had two different sides: front side was more relief, backside was smoother. The inner side of the film had a smoother surface (fig. 1). Ra of polylactic acid films varied from 0.01 to 0.018 μm within the error range from 0.003 to 0.005 μm.

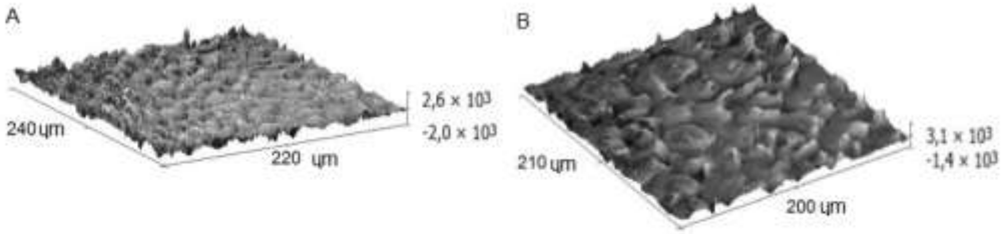

Fig. 1. The polylactic acid films surfaces: a – inner surface; b – outer surface.

The plasma increased the roughness of polylactic acid films by 2.4 times (plasma treatment time was 90 seconds). The asymmetry parameter of all samples was Rsk<|1.5|.

All samples had the left side asymmetry.

The analysis of the obtained data showed that the films had a wetting angle θ = 80 ° and their properties were close to hydrophobic. The surface energy of the films varied in the range of 26-27 mJ / m^2. The contribution of the dispersion component was more significant than the polarization one. The polarity of the polylactic acid films was 0.36. The plasma decreased the wetting angle of the polylactic acid films by 1.5 times.

Conclusion. The polylactic acid films have two different sides: front side was more relief, backside was smoother. The low temperature plasma modification contributes to increase the surface roughness and decrease the wetting angle of the polylactic acid films.

The research was conducted with the financial support of the Russian Foundation for Basic Research (RFBR) as part of the project № 18-315-00048.

MULTILAYER CHROMIUM NITRIDE/CARBON COATINGS DEPOSITED BY MAGNETRON SPUTTERING

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Multilayer chromium nitride/carbon coatings (~0.9 µm) were deposited by magnetron sputtering in Ar atmosphere at 0.2 Pa. This study focuses on the effect of the layer thickness (50, 100, 150 and 225 nm) on structural and mechanical properties of the multilayer coatings.

The crystal structure of the deposited coatings was investigated by X-ray diffraction and Raman spectroscopy. A cubic structure of CrN and an amorphous carbon phase could be identified within the coatings. The increase in layer thickness results in an increase in grain size of CrN from 11 to 53 nm as well as in the occurrence of strains inside the CrN phase. The ratio of I_D to I_G measured by Raman spectroscopy slightly changed from 1.045 to 1.103.

The film morphology is significantly improved (R_a from 12.8 to 23.5 nm) for the thin coatings.

Hardness and elastic modulus of the CrN/C coatings were measured by nanoindentation at a penetration depth up to 0.3 µm. Highest hardness and lowest elastic modulus were measured for the CrN/C coating with a layer thickness of 225 nm.

The coating adhesion to stainless steel substrate was determined by a scratch-test. The resistance to coating chipping of the CrN/C films could be improved from 10.7 to 41.9 N with the decrease in layer thickness.

SYNTHESIS OF NANODIMENSIONAL CARBON FILMS IN HOLLOW CATHODE DISCHARGE

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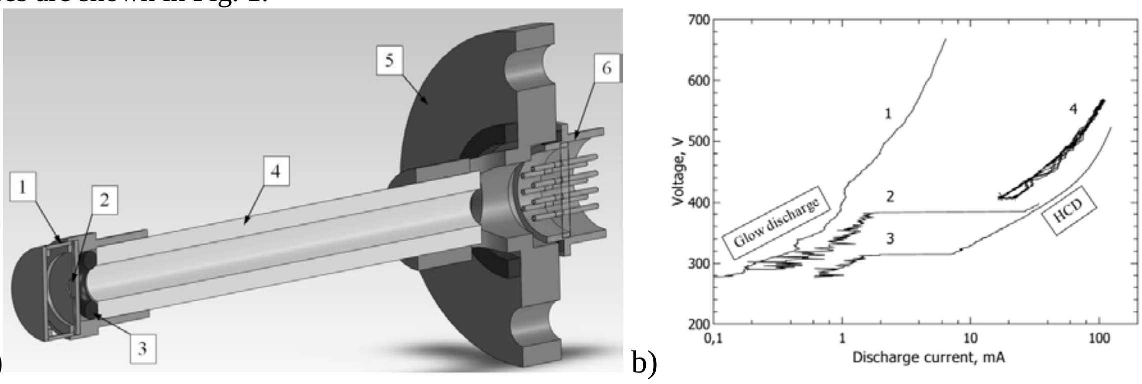
The plasma sources based on the hollow cathode discharge (HCD) are used in a wide variety of applications. The term HCD is applied to plasmas in a cathode with negative curvature geometry. The hollow cathode effect used in the HCD is characterized by electron trapping by the geometry of the cathode resulting to plasma density higher than a common glow discharge (from 10^{11} to 10^{13} cm^{-3}). HCD excites when the distance between cathode surfaces is reduced, while the applied potential and gas pressure are kept constant, or conversely for a given cathode geometry (the gas pressure is increased such that "dp" product is 1 - 10 Torr cm depending on the gas used). Features of the HCD allows to use it, for example: for elemental analysis [1], nitriding [2], vacuum welding [3], plasma-activated pre-treatment and coating processes [4-5], also as efficient sources of light [6], electrons [7], ions [1, 8] etc.

Here, we describe the method of the amorphous carbon films deposition, characterized by the simplicity of the plasma source design. The source is based on the planar HCD for easy variation of the film thickness and crystalline structure. The cathode/sample holder design and the I-V curve of the discharge for various pressures are shown in Fig. 1.



a) b)

Fig. 1. Section view of the cathode/sample holder (a; 1 - cathode/sample holder, 2 - sample, 3 - heater, 4 - ceramic tube, 5 - flange, 6 - electrical feedthrough) and I-V curve of the discharge (b; 1 - 3 - Ar discharge at 9 Pa (1), 12 Pa (2) and 16 Pa (3); 4 - C_3H_8 (27 Pa)).

The I-V curve of the HCD is almost independent of the pressure over a wide range [9]. It allows us to develop the carbon deposition method with a good reproducibility (in this work it was confirmed by Raman spectroscopy and atomic force microscope measurements). Also, HCD allows to deposit a graphite layers with controlled SP^2/SP^3 ratio by three types of discharges [10] with different working discharge voltage (energy of bombarding ions).

As example of the PECVD application of the HCD we represent the synthesis method of nano-crystalline graphite films on Al_2O_3/Ni(111) samples. These films later can be used for testing the modes of heteroepitaxial synthesis of structurally homogeneous graphene for nanoelectronics [11]. The field emission of nano-crystalline graphite was measured. The presence of vertically aligned graphene is revealed.

This work was supported by the Russian Foundation for Basic Research (project no. 19-07-00432).

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THE INFLUENCE OF ION IRRADIATION ON STRUCTURE AND MECHANICAL PROPERTIES OF PRESSED PROFILES OF V95 ALLOY AFTER ARTIFICIAL AGING*

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The effect of 10-20 keV Ar^+ ion irradiation on the mechanical properties and structural-phase state of hot-pressed thin profiles (1.5 mm thick) of V95 (Al-Zn-Mg-Cu) alloy after artificial aging (T = 140ºC, 16 h) was studied.

Irradiation of samples with continuous beams of Ar^+ ions on the equipment for ion-beam implantation (ILM-1) with an ion source PULSAR-1M was carried out. ILM-1 equipment based on a glow discharge with a cold hollow cathode. The ion current density was 300 μA/cm^2 with the ion fluence of $2{\cdot}10^{15}$ and $1{\cdot}10^{16}$ cm^{-2}.

Electron microscopy data (Transmission electron microscope − JEM-200 CX) of thin foils samples were obtained. Foils were prepared from cross sections parallel to the irradiated surface at a distance of ~ 150 μm from the irradiated and non-irradiated surface.

It was shown that ion-beam treatment of the alloy in the used irradiation modes in the absence of significant heating of the samples (T ~ 35-50 °C) was not lead to a change in the tensile strength and yield strength, while the relative elongation increases slightly (by 1-2 %). This result is interesting, because the improvement of plastic properties while maintaining the strength can have a positive impact on the resource characteristics.

Electron microscopic study showed that under the influence of irradiation in the entire volume of samples there is a change in the grain structure. The elongation of the grains disappears, they become equiaxed. In addition, the irradiation leads to the transformation of the form of (Cu,Fe,Mn)Al_6 intermetallic crystallization origin. This is occurred in a decrease of the length of the slats to 0.1-0.2 μm and an increase of the number of equiaxed shape particles with a diameter of 50-70 nm. Irradiation of the samples were not affected on the size and volume fraction of fine particles of strengthening η′- and η - phases.

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EFFECT OF IRRADIATION ON THE STRUCTURE SUBJECTED TO SEVERE PLASTIC DEFORMATION OF THE 1461 ALLOY OF THE AL-Cu-Li- Zn SYSTEM*

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The effect of argon ion irradiation on structural and phase transformations of the 1461 alloy based on the Al-Cu-Li-Zn system subjected to severe plastic deformation (SPD) was studied by transmission electron microscopy.

The samples of the 1461 alloy 2 mm thick were deformed at room temperature and a pressure of 4 GPa in Bridgman anvils to 5 revolutions (angle of the anvil rotation $\varphi = 10\pi$ rad). The thickness of the samples was ~ 400 μm. The samples were irradiated in continuous mode with Ar^+ ions (E = 10 keV, j = 100 μA/cm^2, $F = 6.25 \cdot 10^{15}$ и $2 \cdot 10^{16}$ cm^{-2}) by the ILM-1 implanter with the PULSAR-1M source. During the irradiation, the temperature of the samples was controlled, which did not exceed the value 180 °C at a maximum fluence.

The study of the structure and phase composition of the alloy was carried out by the thin foils method by JEM-200CX and Philips CM 30 Super Twin electron microscopes in the IPM UB RAS Center. Foils were made from samples by electrolytic thinning them on both sides. Thus, the information about the structural condition of the original and irradiated samples from their central part with the distance ~ 200 μm from the surfaces was obtained.

Electron microscopic study was showed that the combined (nanocrystalline + nanofragmentation) structure by SPD was formed. The nanocrystalline structure occupies almost the entire volume, the nanofragmentation structure occurs on separate parts of the sample. Nano-grains were the equiaxed shape with the either straightened or convex-concave boundaries. The diameter of recrystallized nano-grains is comparable to the diameter of nanofragments and varies from 20 to 50 nm. The contrast in the form of arcs or loops near the nano-grains with convex-concave boundaries was revealed. The heterogeneous nucleated particles of the T_2 (Al_3CuLi_5) phase on nano-grains boundaries and on remained fragments of dipole boundaries were observed. The diameter of the particles was not exceed of 5-10 nm.

The transformation of the structure of strongly deformed the 1461 alloy by the irradiation (E = 10 keV, j =100 μA/cm^2, $F = 6.25 \cdot 10^{15}$ cm^{-2}) was caused. Large-scale dislocation clusters in the alloy structure were observed. In some areas, uniformly distributed dense tangles of dislocations was revealed, in others areas occures plexuses with insignificant density. The diameter of nano-grains (from 20-30 to 50 nm) in areas with a high dislocation density by the electron microscopic images was obtained. In areas with low density, there is an almost homogeneous nano-and submicrocrystalline structure with a structural element size of 100-120 nm. Thus, the structure with the bimodal size distribution of nano-grains with low fluence irradiation was formed. The irradiation in this mode was not have a noticeable effect on the decay of the supersaturated solid solution of a strongly deformed alloy.

The increase in ion fluence up to $F = 2 \cdot 10^{16}$ cm^{-2} leads to the formation of homogeneous submicrocrystalline structure with the individual submicrocrystalline diameter of ~ 200-500 nm on the 1461 recrystallized alloy. The sub-microcrystals with straightened the boundaries and the equilibrium triple junctions were obtained. In this case, there is almost complete disappearance of dislocations. The small increase of the size of T_2-phase particles up 10 to 15 nm and the increasing of the density distribution on the volume of the sample with the increasing fluence were occurred.

Thus, it was found, that short-term (10-32 s) Ar^+ ions irradiation leads to the transformation of the microstructure of the 1461 alloy after SPD. The compare of the obtained results with the microstructure formed in this alloy after the traditional low-temperature annealing and the choose of the irradiation modes in order to form the optimal structure and properties of the alloy will be planned.

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THE INFLUENCE OF ION IRRADIATION ON MECHANICAL PROPERTIES AND LOW-CYCLE FATIGUE OF PRESSED PROFILES OF THE V95 ALLOY AFTER ARTIFICIAL AGING*

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The results of previous studies on the effects of ion gas beams on aluminum alloys [1] indicate that ion-beam treatment in addition to the replacement of intermediate annealing can be used to improve the mechanical and resource characteristics of aluminum semi-finished products at the final stages of processing. The favorable impact of ion-beam treatment on the resource characteristics of various materials is evidenced by some literature sources [2-5]. In this regard, it is important to study the laws of modification of the structure, phase composition and functional properties of industrial aluminum alloys in a different initial state (including the state of supply) under the influence of variable modes of ion-beam treatment.

In this paper, the hot-pressed profiles (PR100-23, thickness 6 mm) of high-strength alloy of the Al-Zn-Mg-Cu system after the hardening and artificial aging (T = 140 ºC, 16 h) were selected.

The irradiation of the massive billets of profiles (30 cm long) with continuous beams of Ar^+ ions was carried out by the equipment for ion-beam implantation (ILM-1) with an ion source PULSAR-1M was carried out. The irradiation was carried out on both sides of the samples when they were moved under the ion beam at different speed. When irradiated in mode 1, the energy of ions E was 20 keV, the ion current density j was 400 μA/cm^2, the speed of the target v was 2.5 cm/s, the width of the collimator d was 2 cm, and the ion fluence F was $1{\cdot}10^{16}$ cm^{-2}. In mode 2: E = 40 keV, j = 500 μA/cm^2, v = 1 cm/s, d = 10 cm, F = $9.4{\cdot}10^{16}$ cm^{-2}. The specimen temperature by the chromel-alumel thermocouple was controlled which was welded to the same sample-witness, and connected to the computer system for the measurement of digital signals by the ADAM-4000 module. At low ion fluence of $1{\cdot}10^{16}$ cm^{-2} the temperature did not exceed of 40 °C, at ion fluence of $9.4{\cdot}10^{16}$ cm^{-2} the samples were heated to 180 °C.

In determining the mechanical properties of the profiles in the initial state and after ion irradiation, standard tensile test methods were used (GOST 1497-84). Cyclic tests on the sinusoidal cycle with a loading frequency of 3 Hz were carried out (cycle asymmetry coefficient was −1). The Weller curves in the range of low-cycle fatigue on the basis of up to 10^5 cycles in order to assess the durability of the investigated aluminum alloys were constructed.

It was shown, that the irradiation of Ar^+ ions with the fluence of $1{\cdot}10^{16}$ cm^{-2} was not lead to a change in the tensile strength and yield strength of the alloy, while the relative elongation increases slightly. There is no effect on low-cycle fatigue at the specified irradiation regime. The Weller curves constructed from the test results of the initial and irradiated samples are similar.

The increase in ion energy, ion current density and ion fluence, which leads to the heating of the samples during the irradiation, leads to a significant decreasing in the strength characteristics of the alloy, which was not meet the regulated requirements.

In the future, it is planned to conduct electron microscopic studies by the transmission electron microscopy of the structure and phase composition of the irradiated samples. And also continue to work of the search for optimal modes of the irradiation, which will allow to improve the resource characteristics while maintaining the regulated strength properties of the alloy.

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INFLUENCE OF ELECTROLYTE-PLASMA SURFACE HARDENING ON THE STRUCTURE AND PROPERTIES OF STEEL 40XH *

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Electrolyte-plasma hardening (EPH) is one of the methods of high-speed heating, in which the workpiece is a cathode or anode relative to an aqueous electrolyte. Depending on the heating mode, electrolyte composition, design parameters of the equipment, it is possible to produce hardening, chemical-thermal and thermocyclic processing of materials [1,3]. At the same time electrolytic-plasma hardening is the most economical and productive method. It is characterized by less energy consumption, simplicity of technological equipment and large size of the hardened zone. The advantages of the method are a sufficiently high productivity of the process and the ability to strengthen the details of a large mass and complex profile [3].

We studied the effect of electrolytic-plasma surface hardening on the structure and properties of steel 40KhN in this work,.

Electrolyte-plasma surface hardening of the samples was carried out in a laboratory setup, designed and manufactured in the Research Center "Surface Engineering and Tribology." Samples were tested for abrasive wear using an experimental installation using the “rotating roller - flat surface” scheme in accordance with INDUSTRY STANDARD 23.208-79. University using the standard technique "ball-disc" (international standards ASTM G 133-95 and ASTM G 99) [4]. The wear tracks were studied using the MICROMEASURE 3D station contactless 3D profilometer. The elemental composition of the sample treated in electrolytic plasma was examined on a JSM-6390LV scanning electron microscope (JEOL, Japan), with the addition of an energy dispersive microanalyzer INCA Energy, from OXFORD Instruments. Measurements for microhardness were carried out on the device PMT-3 in accordance with INDUSTRY STANDARD 9450-76.

It was established that after ESP a modified layer with a thickness of 1-1.2 mm with high hardness and wear resistance is formed, consisting of a hardened layer of fine-grained martensite, an intermediate layer of perlite and martensite. It is established that after ESP microhardness and wear resistance of steel 40XH increases, depending on the processing mode. After an ESP with a heating time of 3 second, the microhardness increases up to 2 times, the wear resistance increases up to 30 times. High wear resistance of steels after ESP is associated with the formation of fragmented martensite with dispersed carbides.

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CALCULATION OF HEAT REGIMES FOR A NI-AL SURFACE ALLOY FORMED ON A CARBON STEEL SUBSTRATE WITH A LOW-ENERGY HIGH-CURRENT ELECTRON BEAM

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Heat resistant alloys based on nickel-aluminum are widely used nowadays in engineering technologies, for example, for the aircraft industry. They have high thermal conductivity combined with high strength at elevated temperatures. Abovementioned properties as well as its low density make NiAl alloy ideal for special applications like coating blades in gas turbines and jet engines[1, 2]. Moreover, NiAl alloy possesses the high module of elasticity and high corrosion resistance, which gives an opportunity to use it like corrosion resistance coating.

To form the Ni-Al surface alloy on carbon steel the films of Ni and Al are deposited alternatively on a substrate of carbon steel (0.14-0.22% C; 0.15-0.3% Si; 0.4-0.65% Mn, 0.3%Ni; 0.3% Cr; Fe – balance, wt.%). Then this multilayer system is exposed to action of a low-energy, high-current electron beam (LEHCEB) which induces a liquid-phase mixing of deposited elements. The purpose of the work and, consequently, the calculations carried out was to determine optimal parameters of a LEHCEB for Ni-Al surface alloy formation on carbon steel and to investigate the effect of different thicknesses of layers of Ni and Al on the heat regime of a target. The letter is important because in terms of liquid-phase mixing the thin layers are more preferable, and for simplification of technological process the thicker layers are better.

Calculations were carried out for various multilayered systems with different thickness and numbers of the layers. For instance, the multilayered system of type 1 was three layered system Ni (0.5 μm)- Al (1.52 μm)- Ni (0.5 μm). The multilayered system of type 2 consists of 10 layers of Ni (0.11 μm each) and 9 layers of Al (0.167 μm each). The total thickness of coating deposited in both cases was 2.5 μm.

The melting thresholds for Ni, Al and carbon steel during LEHCEB irradiation were determined by the calculation. The phase diagrams obtained in calculation showed that process of melting occurs similarly for all types of multilayered systems. Melting starts in aluminum layers, then the melt appearing in substrate and finally - in the nickel layers. Layers of aluminum melt successively starting from the next to the irradiated surface. Melting of layers of nickel happens similarly. The calculations demonstrated that the melt thickness on the surface after irradiation with LEHCEB is about 3 μm, and the average lifetime of the melt is ~1 μs (Ni- layers), and ~10 μs (Al- layers).

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ELECTRICAL MODEL OF MICRO-ARC OXIDATION PROCESS*

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Micro-arc oxidation (MAO) is a complex plasma-chemical process of forming protective oxide coatings on metals and valve group alloys. Such coatings are used in many industries: aviation, rocket and space, textile industry, railway and transport engineering, instrument making, medicine, etc. At the moment there are several problems that impede the widespread introduction of this technology, in particular, the lack of knowledge of the phenomena occurring in the MAO process [1, 2].

Currently, there are a large number of works devoted to the mathematical modeling of the MAO process [3] - [6], but all of them describe only certain of its aspects, in particular, the phenomena occurring during the action of micro-discharges are not taken into account. In this paper, a model of the micro-arc oxidation process in the form of an equivalent replacement electrical circuit is proposed, which takes into account both the electrochemical and plasma-chemical processes that occur during MAO treatment, and an analysis of its work is carried out (Fig. 1).

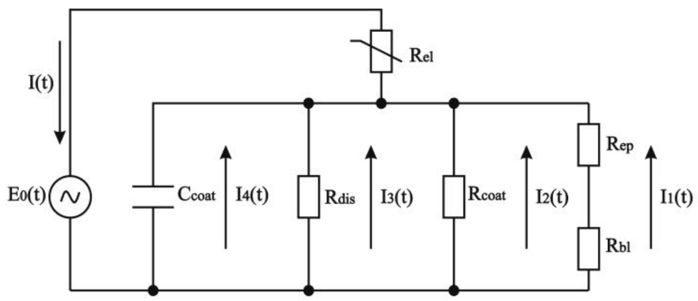

Fig. 1. The modified equivalent circuit of the MOE system: C_{coat} - coating capacity, R_{coat} - coating resistance, R_{bl}, R_{dis}, R_{ep} and R_{el} are the resistance of barrier layer, micro-discharges, electrolyte in the pores and thickness of the electrolyte, respectively; $E_0(t)$ - technological current source voltage, $I_1(t)$ and $I_2(t)$ are the electrochemical oxidation currents, providing growth of the barrier and porous layers, respectively; $I_3(t)$ - micro-discharges current, $I_4(t)$ - coating capacity charge current, $I(t)$ - technological current.

In Fig. 1 C_{coat} is the coating capacity, R_{coat} is the coating resistance, R_{bl}, R_{dis}, R_{ep} and R_{el} are the resistance of the barrier layer, micro-discharges, electrolyte in the pores and the electrolyte thickness, respectively, $E_0(t)$ is the technological current source voltage, $I_1(t)$ and $I_2(t)$ - electrochemical oxidation (ionic) currents, ensuring the growth of the barrier and porous layers, respectively, $I_3(t)$ is the micro-discharges (electronic) current, $I_4(t)$ is the coating capacity charge current, $I(t)$ is the technological current. *Rel* resistance is variable, which allows to take into account the concentration of electrolyte ions change with time (the phenomenon of the so-called "degradation").

The values of the equivalent circuit parameters are calculated on the basis of the fundamental laws of physics and chemistry.

The proposed model, which takes into account both electrochemical and plasma-chemical processes, makes it possible to simulate the MOE system response to various technological parameters changes: current, voltage, shape and frequency of polarizing pulses, MAO process time and electrolyte components concentration.

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ACCELERATION OF HEAVY IONS IN THE HALL ACCELERATOR

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The process of acceleration of heavy ions in the hall accelerator is studied. Numerical solutions of one – dimensional hydrodynamic equations describing a three-component system-neutral particles, electrons and ions-are obtained. Ions move in a collisionless manner and are accelerated by a self-consistent electric field, electrons diffuse across the magnetic field. The self-consistent field is calculated using the Poisson equation, and it is shown that there is no singularity when the ion velocity coincides with the ion sound velocity. This is due to the refusal to use the exact quasineutrality condition (i.e.), see [1,2]. It is also shown that there is a critical magnetic field above which it is impossible to propagate the ion flow.

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EFFECT OF COMBINED TREATMENT ON MICROHARDNESS AND STRUCTURE OF HYPOEUTECTIC SILUMIN*

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Many scientific teams are working to improve the physical and mechanical characteristics of silumin. Multiphase composites based on the Al-Si system are being created [1]. The problems of the influence of plastic deformation on the tribological characteristics of the glory AlSi9Cu3 are investigated [2]. In article [3], the influence of alloying elements and crystallization rate on the structure and mechanical properties of eutectic silumin was established.

The scientific work uses methods of the modern material physics to provide an analytic interpretation of the changes occurring in structure and mechanical properties of hypoeutectic AK10M2N silumin after combined treatment.

The as-cast AK10M2H silumin with the following elemental composition: ((9.5-10.5)Si, (2.0-2.5)Cu, (0.8-1.2)Ni, (0.9-1.2)Mg, (up to 0,6)Fe, (up to 0,05)Mn, (up to 0,05)Ti, (up to 0,05)Pb, (up to 0,06)Zn, (up to 0,01)Sn; the rest is Al, weight %) was used as the research material. The specimens had the shape of a parallelepiped with sides 20×20×10 mm. We used yttrium oxide powder Y_2O_3 as coating material.

The silumin speciments were exposed to the combined processing. The first stage involved application of composite coating of the system Al – Y_2O_3 by the method of electroexplosive alloying using the unit EVU 60/10. During the second stage the resulting coating was treated by high-current pulsed electron beam with parameters as follow: energy of accelerated electrons – 17 keV energy density – 25 j/cm^2 and 35 j/cm^2, pulse duration – 150 μs, number of pulses – 3. Modification of the surface was made using the unit 'SOLO'.

The research material appears to be multiphase and morphologically diverse in its original state, aluminium and silicon-based solid solution being its principal phases. Surface modification of AK10M2N silumin by electroexplosive alloying results in formation of a composite coating of the system Al – Y_2O_3. Thickness of the modified layer is inhomogeneous, the average thickness of the coating varied in the range from 50 μm to 70 μm.

Subsequent treatment by electron beams results in the formation of a homogenized layer. The layer's thickness varies depending on parameters of electron beam treatment and electroexplosive alloying and achieves maximum value of 80 μm (fig. 1). It was shown that microhardness of surface layers of hypoeutectic AK10M2N silumin can increase by 5-8 times depending on the treatment mode.

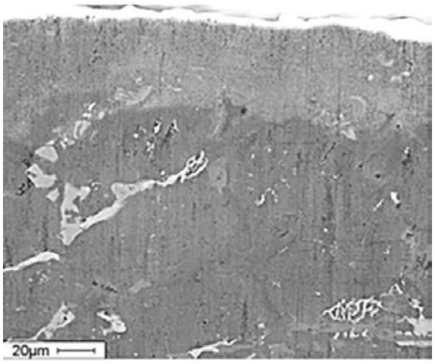

Fig. 1. Electron microscopic image of silumin structure after complex treatment

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COATINGS BASED ON CHROMIUM CARBIDE, DEPOSITED BY ARC SPUTTERING OF GRAPHITE AND CR-AL(SI) TARGETS*

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In the case of joint sputtering of graphite and composite M_xA_y targets, where M - transition metal of IIIB-VIB groups, A - element of the IIIA-IVA groups of periodic system, coating with an amorphous structure is formed [1]. The strong metal-carbon bonds increase internal stresses, reduce ductility and viscosity of coatings. In contrast, doping of carbon coatings with metals that do not form strong bonds with carbon (Cu, Al [2]) is accompanied by the formation of metal phases in the carbon matrix, which improve the viscosity, but reduce the hardness. Nevertheless, it is possible to obtain thermally stable coatings with low residual stress, high hardness and toughness by doping with non-metallic elements, for example, silicon [3]. This paper presents the results of study of CrAlC and CrAlSiC films deposited with physical vapour deposition (PVD) technique.

Transmission electron microscopy (TEM), scanning electron microscopy (SEM) and Raman spectroscopy were applied to investigate the structure of CrAlC and CrAlSiC coatings. The mechanical characteristics (hardness, elasticity modulus), friction and corrosion behavior of coatings were studied.

At the close carbon content in the films, the content of aluminum in CrAlSiC is higher. Despite this, the hardness and H^3/E^2 ratio of CrAlSiC is higher that these values for CrAlC. Friction coefficient of CrAlSiC is 0.04, CrAlC – 0.26. The feature of structure of CrAlSiC coatings leads to improving their mechanical and tribological properties. Structure of both coatings is amorphous-nanocrystalline. The formation in the films of Cr_2Al, Cr_{1-x} Al_x(Si)C and the metastable CrC phases is possible. Cr_{1-x} Al_x(Si)C phase is a result of Cr atoms partially replacement by Al due to the large its amount in coatings. The adding of silicon leads to the formation of silicon carbide nanograins. Nanograins of silicon carbide with a size of up to 30 nm were detected in CrAlSiC using transmission electron microscopy. Clusters of nanocrystalline graphite as spherical inclusions and plates, probably, of several graphene layers were found in CrAlC using Raman spectroscopy. Aluminum oxide, found in both coatings, makes their corrosion-resistant coatings.

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THE AXIAL VUV RADIATION INTENSITY DISTRIBUTION OF A GLOW DISCHARGE AND ITS APPLICATION FOR CREATION LUMINESCENCE CENTERS IN CRYSTALLINE MEDIA *

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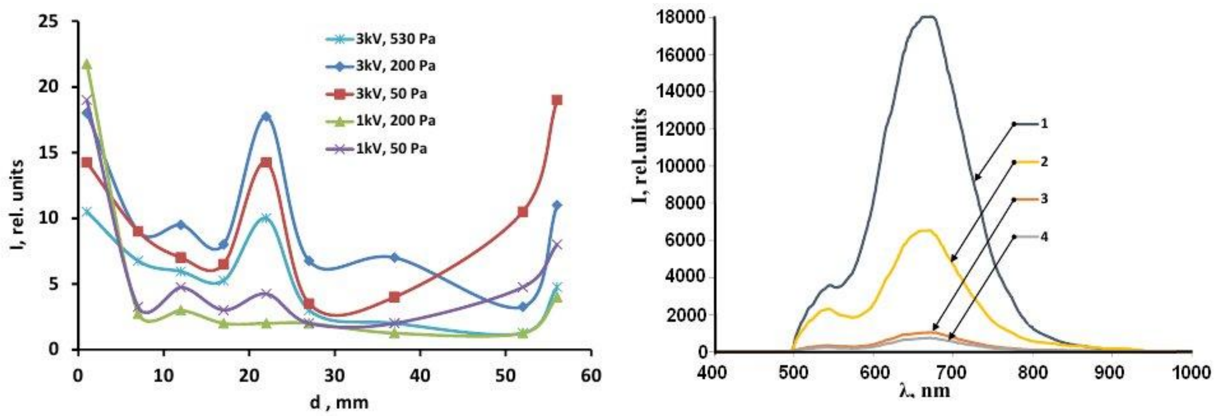
The axial VUV radiation intensity distribution (<130 nm) of an air glow discharge at pressure 50 – 530 Pa was investigated by the thermoluminescent method using the $CaSO_4{\cdot}Mn$ thermoluminophor. The formation of thin layer of luminescent defects on the faces of planar lithium fluoride crystals located in the positive column (low-temperature plasma) and Faraday dark space of a glow gas discharge was studied.

The purpose of the study was to investigate axial VUV radiation intensity distribution of glow discharge at various pressures and voltages for creation color centers in wide-gap crystals. It was necessary to determine the types of the formed color centers, to study the spectral-kinetic characteristics of their luminescence, to reveal the mechanism of their formation and to identify the glow discharge zones in which defect formation was most effective.

Scanning confocal fluorescence microscope MicroTime 200 with picosecond time resolution with a spatially-selective time-correlated single photon counting was used to determine spectral-kinetic characteristics of photoluminescence of lithium fluoride (LiF) irradiated samples bandgap width, which is about 14 eV. Spectra of photoluminescence measured under excitation by picosecond laser with a wavelength of 470 nm were recorded by the spectrometer Ocean Optics 6500.



(a) (b)

Fig. 1. Axial VUV radiation intensity distribution (a) (the anode was located on the left, the cathode on the right) and luminescence spectra (b) of irradiated crystals. (Excitation with picosecond laser pulses at a wavelength of 470 nm, light filter with a transmittance from 500 nm. The curves (1) and (3) contribute to a specimen in the positive column, (2) and (4) – in the Faraday dark space, (1) and (4) – for the anode side (turned towards the anode) and (2), (3) – for the cathode side.)

Using the thermally stimulated luminescence method we obtained the VUV-radiation distribution of the discharge (Fig. 1a). The obtained results give a picture of the distribution of VUV radiation with a wavelength shorter than 130 nm. The VUV radiation intensity distribution has maximum values in the near-electrode regions of the discharge in the pressure range of 50–530 Pa and voltages of 1–3 kV. The stratified positive column of glow discharge is also a region of intense VUV radiation at high voltage.

As follows from Fig. 1b, there are two types of luminescent centers formed in crystal during irradiation in a glow discharge, namely, F_3^+ - and F_2- color centers with luminescence band maxima at 540 and 680 nm and decay time constants of 7.1 and 17.9 ns. By using a MicroTime 200 time resolution laser confocal scanning luminescence microscope (PicoQuant GMBH) it was shown that the highest concentration of luminescent defects corresponds to the sides of the crystals that were irradiated near the electrodes.

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TWO-STAGE SUBNANOSECOND PLASMA SWITCH*

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An experimental investigation of high-current high-voltage switches based on the "open" discharge with the generation of counter-propagating electron beams – kivotrons is carried out. The possibility of operation of such gas discharge devices in a two-stage of nanosecond pulses compression circuit at a voltage up to 25 kV and a repetition rate up to 12 kHz pulses with forced air cooling in the regime of regular pulses at the resistive load of 20 Ohm is demonstrated. The total pulse compression degree in two stages reached 300-600 with pulse edge less than 200 ps. The average power at the active load after the second stage of the compressor reached 500 watts. High efficiency of nanosecond pulse compression in comparison with analogues based on other physical principles is demonstrated. In this work the main operation parameters of the kivotrons in the regime of increased pulse repetition rate are considered and optimized, as well as circuitry features of their operation with cascade connection and a different type of load for each stage of the pulse compressor.

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EFFECT OF ADDITIONAL ION BOMBARDMENT ON THE QUALITY OF VACUUM ION-PLASMA COATINGS

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The characteristics of multilayer vacuum ion-plasma coatings Ti-TiN are investigated. It is shown that additional ion bombardment contributes to obtaining high-quality coatings. Ion bombardment has a significant effect on the state of the surface layer of the metal. In the process of ion bombardment, conditions are created for the formation of active adsorption centers and fine-grained structure, nanoscale grains and layers [1,2].

The characteristics of the surface quality with a vacuum ion-plasma coating under conditions of ion bombardment largely depend on the initial surface, as well as on preliminary preparation before deposition of coatings [2, 3].

The purpose of this work is to study the effect of additional ion bombardment (AIB) at the stage of preliminary surface cleaning and deposition of coatings on the adhesion strength of synthesized coatings of the Ti-TiN system.

To implement additional ion bombardment, a «PINK» plasma source was used, which implements a non-independent high-current diffusion discharge. It was used both at the stage of pretreatment and surface activation, and for the synthesis of protective coatings in the plasma assisting mode. The use of «PINK» allows you to significantly increase the adhesive strength and form a better coating, as well as to reduce the temperature of the formation of layers.

The formation of multilayer coatings is implemented by sequential deposition of Ti and TiN from arc plasma.

Conducting AIB plasma source of «PINK» allows you to: provide high energy efficiency of the process of generating low-temperature bulk plasma; reduce the fraction of the micro-droplet fraction in the plasma flow of vacuum electric arc evaporators; perform plasma cleaning, etching and surface activation without spraying with cathode material vapors; realize complex processing of products in a single vacuum cycle, including the processes of final cleaning, activation, plasma-assisted spraying of functional coatings; to ensure the formation of micro- and nanostructured coatings with high hardness, increased wear resistance, improved corrosion resistance.

The adhesion of the coating material to the base was investigated by two methods: - by bending of witness samples and - by the imprint of a diamond pyramid when measuring microhardness. Tests showed excellent adhesion of the deposited coatings. In the first case, when bending a stainless steel plate, there were no chipping and peeling of the surface layer at the bend site. The interaction of the diamond pyramid with the surface on which the coating was based on carbon and silicon was also not observed detachment and chipping.

The resulting surface layers have high adhesion and are able to withstand repeated bending, which was confirmed on samples of witnesses.

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DESIGNING OF EQUIPMENT FOR THE SYNTHESIS OF COATINGS FROM NITRID AND CARBIDES OF INTERMETALLIDE TI - AL SYSTEMS BY CONDENSATION OF PLASMA FLOWS GENERATED WITH VACUUM ARC

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The formation of new materials of coatings with high physicochemical properties on the surface of parts and the development of technologies for their deposition is one of the promising areas of industrial development. Such materials include multicomponent materials based on intermetallic compounds, which have unique properties and retain an ordered structure up to the melting temperature. The Ti – Al system is one of the most promising in the field of creating nanostructured metal-intermetallic composites, primarily due to the low density of raw materials and their wide use in engineering.

The article discusses the results of research on the production of coatings formed by a vacuum arc with an integral cold cathode. The results of the interaction of titanium and aluminum flows on cold and hot substrates in the environment of various gases are analyzed.

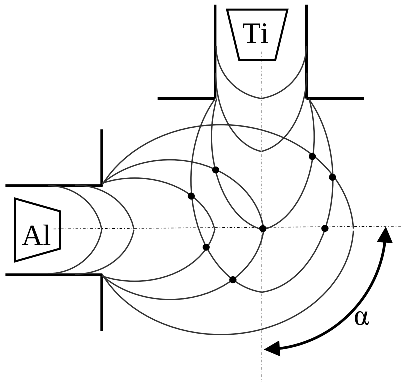

Fig. 1. The scheme of the experiments

Analysis of the research results [1-6] showed that the phase composition of the coatings on the samples, namely, the percentage of intermetallic, as well as their carbides and nitrides in the coating depends on (Fig. 1):

• spatial location of samples (distance to electric arc evaporators, angle between plasma axis and substrate surface);

• additional bombardment of the substrate surface with ions of the reaction gas;

• processing modes (the ratio of the arc current Ti and Al evaporators, respectively, pressure, ion energy).

The obtained data will make it possible to formulate a technical assignment for designing installations for the synthesis of coatings from nitrides and intermetallic carbides of Ti-Al systems of the required phase composition.

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GENERATION OF THE COLD PLASMA JET OF ATMOSPHERIC PRESSURE IN HELIUM AND ARGON*

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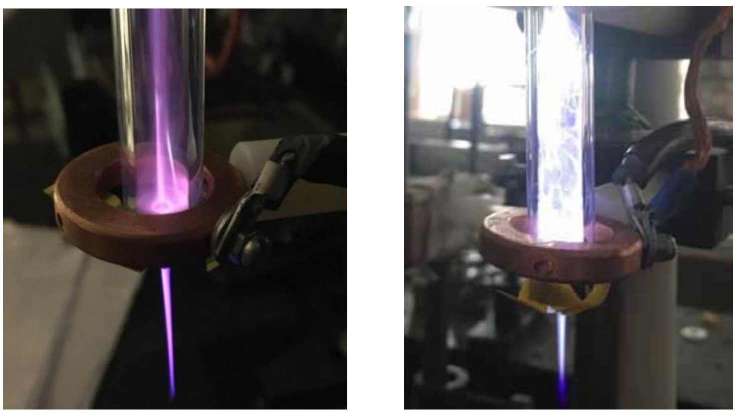
The results of an experimental study of the generation, spectral and temperature parameters of a plasma jet, which was generated in a dielectric channel in a stream of inert gas — helium or argon, propagating in a gas stream outside the channel, are presented. Gas-discharge device consisted of a quartz tube channel 100 mm long with an inner diameter of 8 mm, in which a metal electrode was coaxially placed, and replaceable capillary inserts 6 mm long with an inner diameter 0.9, 1.5, 2.3, 2.6, 3.2 or 3.77 mm. Outside the quartz channel, there was a movable copper ring electrode. The discharge zone was formed by potential – loaded and external grounded electrodes. The gas system provided the flow of working gases with typical flow rates of 0.5–10 l/min with an overpressure in the gas line of 1.5 atm. A sinusoidal voltage with a frequency of 15-30 kHz and an amplitude of up to 6 kV was used. When the working gas was pumped and the voltage *U* was applied between the loaded and grounded electrodes, a breakdown was observed at a positive half-wave and with further increase of *U* over 1 kV in helium and 3 kV in argon a plasma jet was formed, which was a sequence of streamers that fell out of the dielectric channel and propagated in a free space.



a *b*

Fig. 1. Photos of plasma jet in helium (a) and argon (b)

Studies were carried out to the dependence of the geometric parameters of a plasma jet in space on the geometry of the dielectric channel and capillaries, the flow rate and voltage in order to increase the volume of plasma formation. Spectral studies measuring the emission of a free jet of helium or argon showed the presence of intense N_2, N_2^+, NO, OH lines, Balmer series lines of hydrogen and helium or argon lines in plasma volume. The spectral composition of the mixture varied with the interaction of the jet with objects of different nature. Temperature measurements showed that the jet raised the temperature in the zone of contact with the surface by a fraction of a degree and it didn’t not exceed 40ºC.

*This work was supported by Russian Foundation for Basic Research, project No.18-08-00510

EFFECT OF COLD PLASMA JET OF ATMOSPHERIC PRESSURE IN HELIUM ON LUNG HUMAN ADENOCARCINOMA CELLS*

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The results of an experimental study of the effects of a cold plasma jet generated in a dielectric channel in an inert gas flow - helium on human lung adenocarcinoma A549 cells are presented.

The discharge device was a quartz coaxial channel 100 mm long with a diameter of 8 mm with an internal electrode and a capillary 6 mm long with a diameter of 2.6 mm. The discharge zone was formed by potential – loaded and external grounded electrodes. The gas system supplied helium at a gas flow rate of 0.5–5 l/min. When the working gas was pumped and a sinusoidal voltage was applied at a frequency of 25 kHz and an amplitude of up to 6 kV, a breakdown was observed between the loaded and grounded electrodes on a positive half-wave, and with a further increase of U over 1 kV a plasma jet was formed in the helium flow. The plasma formation spectrum was characterized by the presence of intense N_2, N_2^+, NO, OH lines, Balmer series hydrogen lines and helium lines in the plasma. The jet increased the temperature in the contact zone with the surface by fractions of a degree and it did not exceed 40ºC.

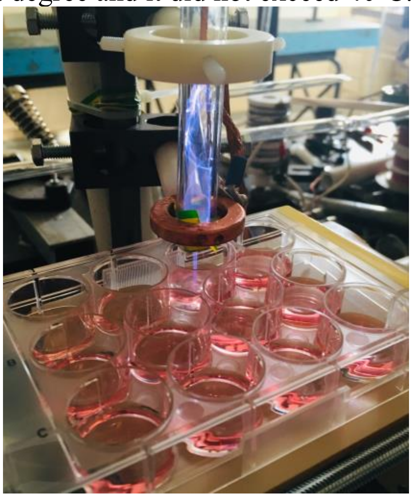

Fig. 1. Photos of the effects of plasma jet in helium on biological objects.

Experiments have shown that human A549 lung adenocarcinoma cells grown in culture dishes were subjected to cold plasma jet ionization (helium) during of 5 to 120 seconds under 3kV and 2.5 L/min argon gas flow. The decreasing of cell viability was observed in plasma-treated cells after 24 h of treatment. This effect was time-dependent with highest value for the cells of 2 min of plasma application.

*This work was supported by Russian Science Foundation, research project No.19-19-00255

RADIATION-AND-THERMAL EXPOSURE OF ACCELERATED IONS ON FERROMAGNETIC ALLOYS OF $Fe_{100-X}Mn_X$ and $Fe_{100-X}Cr_X$ AFTER THEIR MEGAPLASTIC DEFORMATION IN COMPARISON WITH PURE THERMAL EXPOSURE*

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In [1], an anomalous acceleration of atomic delamination was observed at warm ($T < 0.3\ T_{melt}$) ultrahigh megaplastic deformation in rotating Bridgman anvils and a ball mill. The accelerated delamination induced by deformation at 573 K is compared with irradiation by high-energy electrons in a close temperature range. This effect is explained by the mechanism of dynamic aging caused by the continuous generation of a large number of moving point defects in the bulk of the material. In the course of high-energy irradiation, the process of defect formation permeates the entire volume of the studied targets and the classical migration mechanisms of radiation physics can be used to explain.

Recently, numerous studies (see review [2]) have established the important role of nano-scale dynamic effects in the effect of ionizing radiation on condensed matter. These effects, which take place during irradiation with accelerated ions (as well as reactor neutrons, fission fragments), remain outside the field of vision of classical radiation physics. They are not related to the migration process of defects, since, for example, the paths of heavy ions with energies from several units to several tens and hundreds of keV in condensed media do not exceed 1 μm. At the same time, the scale of their impact over the depth of targets reaches values from several tens and hundreds of micrometers to several millimeters. The temperature of the initiated processes decreases by tens and hundreds of degrees as compared with the thermally activated processes and, despite this, their speed increases by several orders of magnitude in the whole volume of the substance, where ions do not penetrate and there are no defects.

The authors of [2, 3] associate these effects with the processes of explosive energy release in the areas of passage of dense cascades of atomic displacements with the formation, within trillionths of a second, of nanoscale zones (thermal spikes) with gigantic temperatures and pressures ($T = 3000 \div 6000$ K, $P = 5 \div 40$ GPa), in some cases exceeding the theoretical yield strength of materials. As a result, these zones emit post-cascade powerful elastic and shock waves, capable of carrying out liquid flow of condensed media on their front, initiating structural-and-phase transformations. Radiation-shaking of a medium by post-cascade waves can play the role of temperature, increasing the mobility of atoms without heating the medium.

In view of the above, experiments were designed and carried out to study the behavior of highly nonequilibrium (metastable) media under conditions of purely thermal exposure and under conditions of ion beam irradiation with accurate reproduction of thermal exposure modes. Samples of $Fe_{100-x}Mn_x$ (x = 4 ÷ 10) and $Fe_{100-x}Cr_x$ (x = 12 ÷ 22) alloys were subjected to cold ($T \sim 0.2\ T_{melt}$) and warm ($T < 0.3\ T_{melt}$) ultrahigh (mega plastic) deformation in rotating Bridgman anvils and ball mill. Comparison of purely thermal and radiation-thermal effects (beams of heavy accelerated radiation: Ar^+, Kr^+ and Xe^+ with energies of 5 ÷ 40 keV) using temporal diaphragms (τ = 0.001, 0.01 and 0.1 s) showed that the formation of the short-range atomic order in initially metastable alloys $Fe_{100-x}Mn_x$ and $Fe_{100-x}Cr_x$ are accelerated many times during radiation-and-thermal of accelerated ions exposure compared to purely thermal.

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MICRODIFRACTIONAL ANALYSIS OF THE STRUCTURE OF HIGH-SPEED CELLULAR CRYSTALLIZATION OF SILUMINE*

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The purpose of this work was to establish the laws of the formation of the structural-phase state of hypoeutectic composition silumin subjected to irradiation by an intense pulsed electron beam. Silumin AK10M2N was used as the study material. The silumin subjected to electron-beam treatment at the "SOLO" setup [1] with the following parameters: the energy of accelerated electrons is 17 keV; electron beam energy density of 25 J / cm^2; irradiation pulse duration 150 μs; number of pulses 3; pulse repetition rate 0.3 s^{-1}. Irradiation was carried out in argon plasma at a pressure of 0.02 Pa. Studies of the elemental and phase composition, defective substructure of silumin samples in the cast state and after irradiation with an electron beam were carried out using transmission diffraction electron microscopy (JEM 2100F).

It has been established that, in the cast state, the material under investigation has a multiphase structure, represented by aluminum-based solid solution grains, eutectic grains, and intermetallic inclusions. The presence in the material of inclusions plate and needle shape significantly reduces the performance characteristics of the material [2]. The irradiation of silumin with an electron beam leads to the melting of the surface layer up to 35 μm thick and to the dissolution of inclusions of the second phase. Subsequent high-speed crystallization is accompanied by the formation of a cellular structure (Fig. 1, a). Nanosized particles of the second phase are located in the volume of cells and along their boundaries (Fig. 1, b – d). It is shown that the formation of a submicro-nanoscale multiphase structure leads to an increase in the wear resistance of the material by ≈1.7 times, microhardness - by ≈1.2 times.

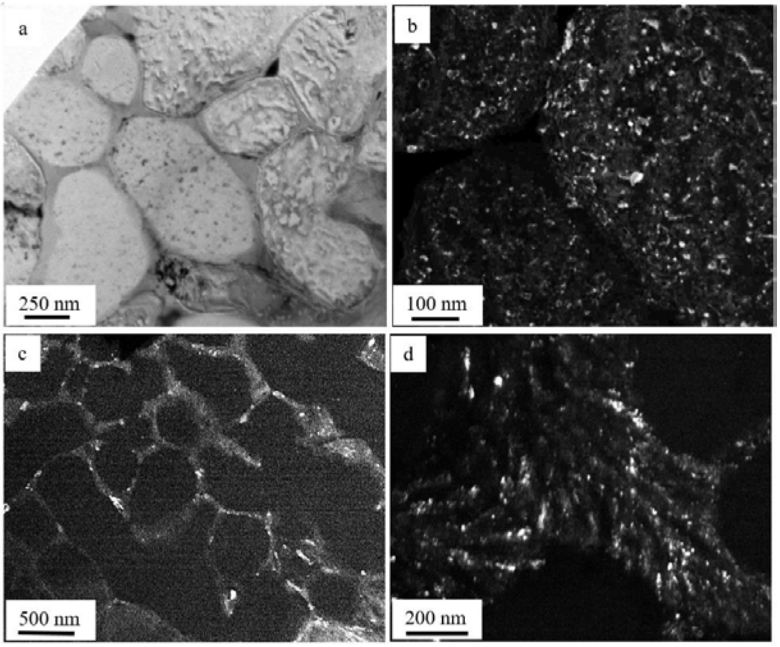

Fig. 1. Electron-microscopic image of silumin structure subjected to irradiation by an intense pulsed electron beam; a - bright field; b –d dark fields obtained in silicon reflexes.

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GASEOUS DISCHARGE PLASMA SWITCHING IN OVERSIZED INTERFERENCE MICROWAVE SWITCHES*

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The report presents the results of the experimental study of gaseous discharge plasma switching in interference oversized switches of X-band active resonant compressors. Switching in the spontaneous breakdown mode was initiated by considerable discontinuity at an electric field antinode in the switching arm. The study was conducted for the interference switch made of the rectangular waveguide with the cross section area of 50×25 mm2 [1] and for the switch with the combination of the rectangular waveguide of 50×25 mm2 cross section and the circular waveguide having the diameter of 50 mm [2]. At plasma gas-discharge switching the threshold nature of effective acting initiated by discontinuity in the form of a thin copper wire introduced into the arm through the cut-off frequency waveguide was found. The switching efficiency as a function of the wire length was determined. The conditions for effective switching with the sequential cascade of the oversized switches are obtained. It is shown the effective switching in oversized interference microwave switches is possible and may be identical to switching in the single-moded switches.

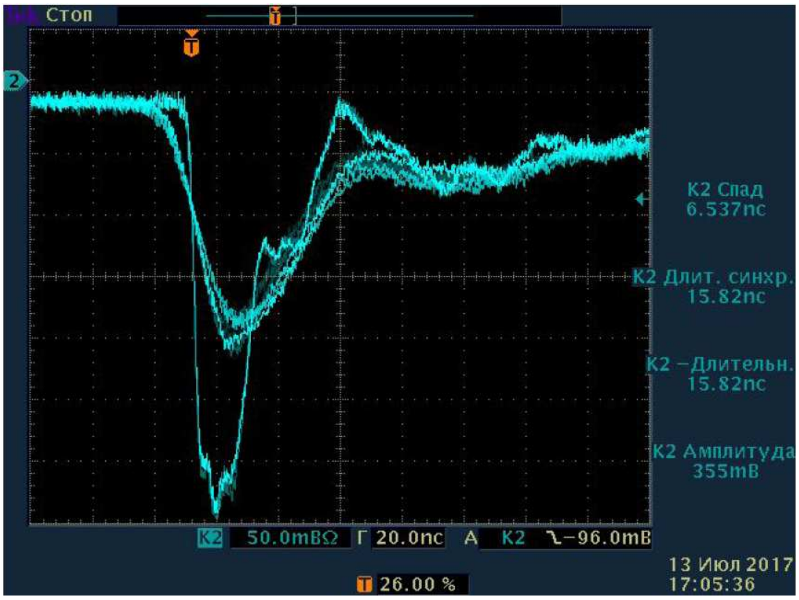

Fig. 1. The oscillogram showing the change in the parameters of the output pulse of the active resonant microwave compressor when the threshold is passed. The interference switch was made of oversized waveguides

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STUDY OF METAL POWDER RECEIVED BY PLASMA SPRAY

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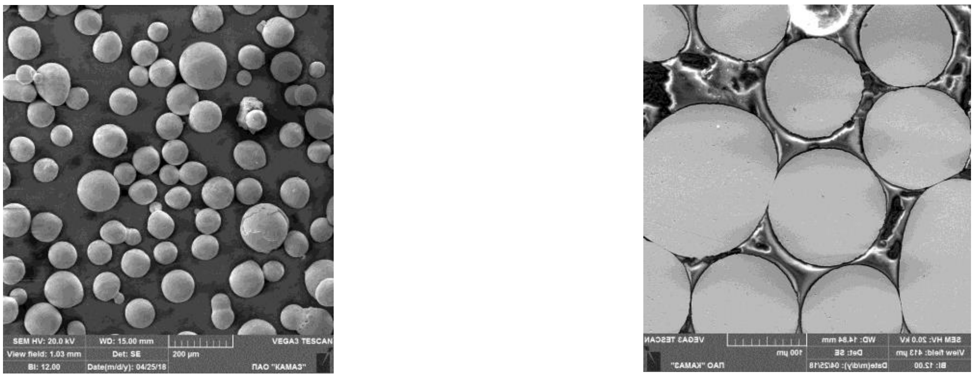
Additive technologies make it possible the production of complex in form and non-technological products at the present level of development of the industry, using universal equipment. Additive technologies are recognized by the leading countries in the world as the main advanced industrial technologies. The Russian Federation has significantly lagged behind in the development of additive technologies from the United States, Japan, Europe, China and Israel. In the medium term, Russia risks becoming dependent on advanced industrial technologies of Western countries and losing its technological sovereignty. In this regard, the development of this technology in our country and the production of raw materials for additive equipment (powders) is today an urgent task.

The problem of obtaining metal powders of various nomenclatures with the required properties can be solved using a highly concentrated heat source, in particular, a plasma jet. A distinctive technological feature of the use of a plasma jet is a higher concentration of the energy of the heating source and its forceful effect on the heating zones. At the same time, the influence of plasma characteristics on the properties of the sprayed materials is obvious.

In this paper, a new method for producing metal and ceramic powders by plasma spraying of rod blanks is proposed. A distinctive feature of this method is the use of a direct-acting plasmatron, where a bar-stock acts as one of the electrodes, and the cooling of the molten particles takes place with a water screen. The water screen is not only in the lower part of the installation, but also flows evenly from the walls, which gives a more efficient cooling of all molten particles, forming a regular spherical shape, and a plasma flow. Water constantly circulates in a closed circuit, the heat is removed in a heat exchanger.

Figure 1 shows of a powder sample obtained by plasma spraying:



×200 ×500

Fig. 1. The powder sample obtained by plasma spray.

The plasma spraying makes it possible to obtain a metal powder size of 5-200 microns.

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APPLICATION OF LOW-PRESSURE GLOW DISCHARGE IN TRANSVERSE SUPERSONIC GAS FLOW

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Article presents application of glow discharge at low pressures in transverse supersonic gas flow limited in part of discharge region. Mathematical model of supersonic flow in a vacuum chamber described. Results of experiments on realization of glow discharge at low pressures due to the organization of a transverse supersonic gas flow are given.

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INFLUENCE OF DIFFERENT PLASMA INITIATION WAYS ON OBTAINING ULTRADISPERSED SILICON CARBIDE

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Silicon carbide (SiC) has been used in many fields of human activity: power electronics, the production of abrasive materials and ceramic products for working in corrosive environments. SiC is used due to its properties: high hardness and wear resistance, wide forbidden zone, refractory [1-2]. The characteristics of the materials can be improved by using nanoparticles in their production.

Silicon carbide synthesis techniques are not effective enough, because they have unsatisfactory dispersity, high duration and other. The synthesis of ultradispersed SiC was carried out on a coaxial magnetoplasma accelerator (CMPA) [3]. This work is aimed at studying influence of different plasma initiation ways on the phase composition of the SiC. It was assumed that the method of initiation of the arc discharge will affect the phase composition of the synthesis product by changing the time and nature of the transition of the mixture of precursors to the plasma state.

The series of experiments were conducted with a different plasma initiation ways: carbon fibers and graphite aerosol (graphitization) . The precursors in experiments were carbon black and silicon powder, which were mixed. Power to the accelerator was supplied from a capacitive energy storage device. The results of experiments were the production of powdered products, which were studied by X-ray diffractometry (XRD) and transmission electron microscopy (TEM).

The result of this work is the optimization the plasma dynamic synthesis of nanoscale cubic silicon carbide using different plasma initiation ways. According to XRD and TEM, the SiC plasma dynamic synthesis proceeds more fully in the case of using graphitization as a plasma initiation way due to the more effective sublimation of precursors during preionization time. In this case product contains a phase of cubic silicon carbide β-SiC (~99%). Important advantage of the graphitization way is the high processability, which ensures the simplicity of the accelerator preparation and the reliability of its operation.

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OBTAINING NANO-DISPERSE SOOT FROM ORTHOXYLENE BY THE HIGH-VOLTAGE AC PLASMA TORCH*

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Carbon structures are used as a reinforcing component in the production of rubber and plastics. About 70% of all manufactured soot is used in the production of tires, ~ 20% is used in the production of rubber products. The remaining amount is used as a black pigment; retarder aging plastics; component that gives plastics special properties.

There are several industrial methods for producing soot. The basis of all is thermal (pyrolysis) or thermo-oxidative decomposition of liquid or gaseous hydrocarbons. Depending on the raw materials used and the method of its decomposition, the following types of soot are distinguished: furnace, lamp, thermal and channel. High quality carbon and fullerene-containing soot are the result of plasma pyrolysis of hydrocarbons. In most cases, DC torches are used for this; however, high-voltage [1] and low-voltage [2] AC devices can also be used to solve these problems. These plasma torches showed high efficiency in the processing of biomass [3], natural gas [4] and organochlorine substances [5].

The report discusses the continuous process of soot production using an AC high-voltage plasma torch. It consists of three electric arc channels with three graphite rod electrodes [6]. The plasma torch is powered by an alternating current power source with a 10 kV open circuit voltage [7]. The power supply consists of a high-voltage transformer (380/10000 V), current-limiting inductances, a reactive power compensator and a system for continuous measurement of electrical parameters. The main plasma gas is argon. Evaporated orthoxylene (boiling point is 144.4 °C) was fed to the heated argon stream. The reagent flow rates were as follows: argon - 1 g/s, orthoxylene - 0.1 g/s. In electric arc channels, the hydrocarbon quickly decomposes to soot. The properties and composition of produced carbon structures were studied using a FT-IR spectrometer, a scanning electron microscope, an elemental analyzer (CHNS), and an X-ray diffractometer. The particle size distribution was determined by the method of dynamic light scattering. It was found that in the products there are two fractions: the main fraction with a concentration of about 70% and a particle size of from 80 to 120 nm and the second fraction with a particle size of from 200 to 1500 nm. The first fraction is the product of the thermal plasma decomposition of orthoxylene, and the second fraction is formed as a result of the erosion of graphite electrodes.

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THE INFLUENCE OF THE MAGNETIC FIELD IN ION NITROGENING ON PROBE CHARACTERISTICS, MICRO-HARDNESS AND STRUCTURE OF AISI M2/R6M5 STEEL

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Ion nitriding is one of the effective ways of surface hardening of steels [1]. In the temperature range of 450-550 ° C, the process is carried out with long exposures. This is due to the low rate of diffusion of nitrogen into the material. The diffusion rate can be significantly increased by various methods of intensifying the process [2, 3]. It is known [3] that the use of a magnetic field in nitriding in a glow discharge allows one to increase the energy of charged particles in a plasma. This accelerates the process of interaction of ions and nitrogen atoms with the surface of the material.

In this work, we study the effect of a magnetic field on nitration in a glow discharge on probe characteristics, microhardness, and the structure of AISI M2 steel. Using a magnetic field on nitration in a glow discharge increases the surface hardness and thickness. Experimental probe current-voltage characteristics in a glow discharge with magnetic fields are obtained.

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THE INFLUENCE OF THE MAGNETIC FIELD IN ION NITROGENING ON PROBE CHARACTERISTICS, MICRO-HARDNESS AND STRUCTURE OF AISI 321/08H18N10T STEEL

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Ion nitriding is one of the effective ways of surface hardening of steels [1]. In the temperature range of 450-550 ° C, the process is carried out with long exposures. This is due to the low rate of diffusion of nitrogen into the material. The diffusion rate can be significantly increased by various methods of intensifying the process [2, 3]. It is known [3] that the use of a magnetic field in nitriding in a glow discharge allows one to increase the energy of charged particles in a plasma. This accelerates the process of interaction of ions and nitrogen atoms with the surface of the material.

In this work, we study the effect of a magnetic field on nitration in a glow discharge on probe characteristics, microhardness, and the structure of AISI 321 steel. Using a magnetic field on nitration in a glow discharge increases the surface hardness and thickness of the hardened material layer by 1.5 times. Experimental probe current-voltage characteristics in a glow discharge with magnetic field are obtained.

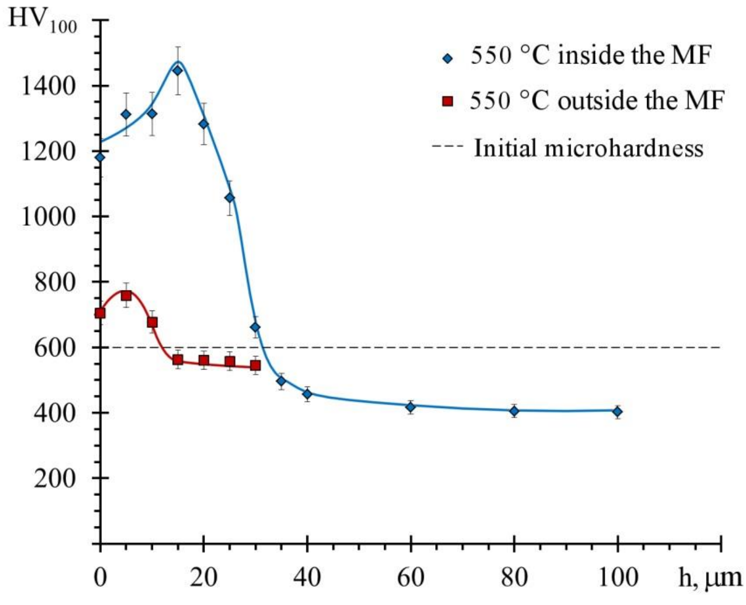

Fig. 1. Graph of microhardness distribution by depth of samples nitrided at 550 ° C

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MODELLING OF MOSSBAUER SPECTRA OF LAYERED METAL SYSTEMS OBTAINED BY ION-PLASMA SPUTTERING

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Ion-plasma deposition allows the formation of layers with high adhesion and the necessary chemical composition. Equilibrium diagrams [1] of the binary systems Fe–Sn and Fe–Zr are characterized by the existence of regions of the solid solution α-Fe(Sn) and α-Fe(Zr) with various intermetallic compounds with increasing of temperature.

High corrosion resistance in combination with mechanical strength, high melting point and low effective cross section for the absorption of thermal neutrons have recently made extensive use of Zircaloy (alloy of Zirconium with Iron and Tin) in reactor engineering. The study of thermally induced phase formation in layered systems Sn-Fe and Zr-Fe is relevant. Simulation of the phase state in layered systems will make it possible to predict changes during thermal treatment.

The layered systems based on Iron, Tin and Zirconium are considered. Using the MSTools software package [2], the spectra of Iron and Tin nuclei were obtained for each position in the phases of binary systems, and taking into account the occupancy of the positions, the standard spectra of each phase were modeled. Next, using the lever rule, the spectra of alloys with different concentrations of the second component were calculated for the reference points of the state diagrams (see Fig.1). A comparison of the simulated spectra with the experimental Mössbauer spectra of two-layer systems (Zr-Fe and Sn-Fe) and the three-layer system Sn-Zr-Fe, obtained by ion-plasma sputtering and subjected to thermal annealing, showed a good correlation.

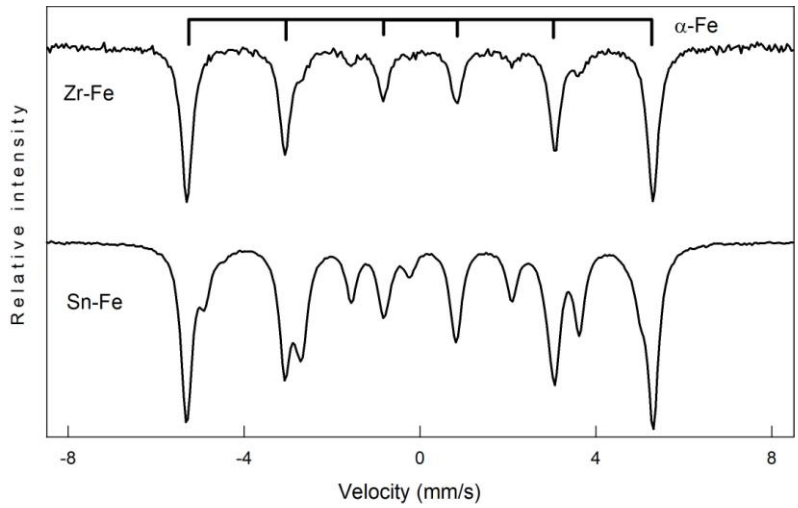

Fig. 1. Simulated spectra of binary system alloys

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EXPERIMENTAL DETERMINATION OF THE OPTIMAL FOCUSING ZONES FOR LASER IGNITION OF BUTANE-AIR COMBUSTIBLE MIXTURES

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Laser ignition is widely discussed and investigated subject today. Recently, in this area of research significant progress has been made. Though laser spark plugs already have practical application, nevertheless the main aspects of ignition of fuel mixtures by means of the laser, for example, the most advantageous position of focus in combustion chamber not fully explored. There are two modes of focusing of laser beam in combustion chamber: focusing in air in the volume of the chamber and focusing on the ablator. Fuel ignition at the first mode of focusing requires high power consumption, increasing the cost and the sizes of laser spark plug, at the second mode of focusing of energy of laser pulse for ignition of fuel it is required 10 times less, however the resource of the ablator is obstacle for realization of this method in practice. Therefore it is necessary to investigate the optimal zone for focusing of laser radiation in which it is possible to realize low energy-intensive ignition and at the same time without destroying the ablator.

In the work results of experiments on ignition fuel mixture (butane based) compositions with various equivalence ratios ($\varphi \sim 0.4$-1.1) and pressures ($p \sim 1$–3 bars) depending on the position of the focus ($l \sim 0$-12 mm) in combustion chamber concerning the ablator are presented. The change in the minimum energy of the laser pulse required foe ignition the fuel mixtures is fixed and also with use shliren's method dynamics development of burning core and propagation of shock wave at laser ignition (1064 nm, 12 ns) was investigated. It was revealed that the optimum zone of focusing of laser radiation where energy of laser pulse accepts the minimum values, was not on the ablator, and in some removal from it.

The received results are of interest to use of laser ignition in the practical purposes.

ACTION OF SUBNANOSECOND PULSED ELECTRIC FIELD ON SCOV-3 AND JURKAT CELLS*

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The effect of the pulsed electric field of the subnanosecond range on human tumor cells Scov-3 and Jurkat is studied. Studies of the effects of nanosecond electric fields on cells are widely carried out [1], but there is no data on the effect of the duration of the pulse rise time on the processes leading to cell death. The use of pulsed electric fields with a subnanosecond rise time can effectively affect the internal structures of the cell, since the polarization time of the outer cell membrane is ~ 1 ns. These fields can be used in the development of new methods for the treatment of human tumor diseases.

The experimental setup (Fig. 1) consists of a coaxial waveguide with a 50 Ω matched load, a transmission line, and a pulse voltage generator. Cell culture with a volume of 0.15 ml in suspension or on a substrate is placed in the end part of the waveguide. The source of voltage pulses is the FID2/25 generator. Pulse duration is 7 ns, amplitude +/- 12..25 kV, voltage rise time 150 ps, frequency up to 3 kHz. Trigger generator G5-26 is used. Measurements of the electric field parameters in the transmitting cable and in the working volume were carried out using wideband capacitive dividers. The amplitude value of the electric field strength in a cuvette is 15..30 kV/cm. The pulse shape is in Fig.2. The absence of electrical discharge phenomena was controlled by spectral radiation registration with use of spectrometer Ocean Flame-S. The geometry of the mismatched part of the waveguide and the cell with the sample provides the passage of high-frequency TEM-wave modes up to 3 GHz into the working volume without noticeable distortions.

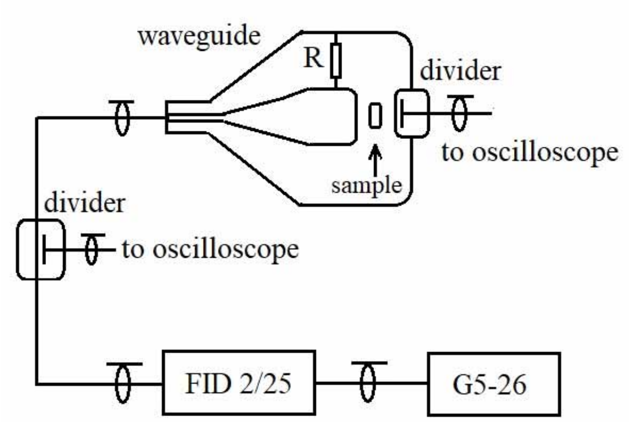

Fig. 1. Experimental setup

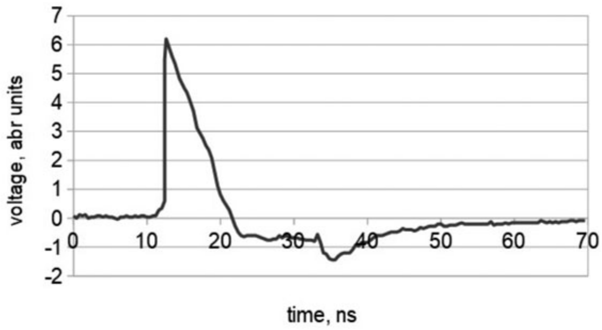

Fig. 2. Pulse shape in sample volume. Amplitude 25 kV/cm

In preliminary experiments, Jurkat and Scov-3 cells were processed at a pulse frequency of 100 Hz. The amplitude value of the electric field strength in the cuvette was 25 kV/cm. The total number of pulses during the processing of each sample was 30000. After the treatment, the stability of the cells was studied using trypan blue staining. The proportion of dying cells was measured after 4 hours, 24 hours and 4 days after treatment.

In experiments on Scov-3 cultures, it was shown that the following day, no more than 50% of living adherent cells remain. In experiments on Jurkat after a day, the concentration of living cells is 90% of the control sample. Authors would like to thank FID Technology for technical help.

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INFLUENCE OF HYDROGEN PLASMA ON THE SURFACE OF A BISMUTH SINGLE CRYSTAL

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Currently, there is an intensified search for new technologies and methodologies that allow creating three-dimensional ordered structures from nanoobjects. Two main parameters are distinguished for create a relief on the surface: injury in plasma and liquid chemical etching. Experience shows that the plasma-chemical effect is always accompanied by the formation of some morphology on an atomically clean surface. In this paper, an attempt was made to plasma processing in chemically active gaseous media in order to modify the nanomorphological surface of bismuth crystals. A bismuth single crystal was a stream of atomic hydrogen (AH). In the experiments was used hydrogen of 99.995% purity. Hydrogen dissociated on the radical with a concentration of active particles is the result of a high-frequency electric discharge. A sample of a bismuth single crystal was treated with atomic hydrogen for an hour.

The crystals surface where smooth and uniform before the visible. As a result of exposure by AH to the surface of bismuth single crystals, formations are formed in the form of protruding submicron and nanoscale particles in the form of single and accumulated triangular pyramids. The angles between the base areas of the pyramidal structure are ~ 60 °, i.e. they go along the binary axes of the single crystal. The angle of inclination of the single crystal is ~ 54° – 56 °, which corresponds to the inclination of granite to a less perfect cleavage of the bismuth single crystal.

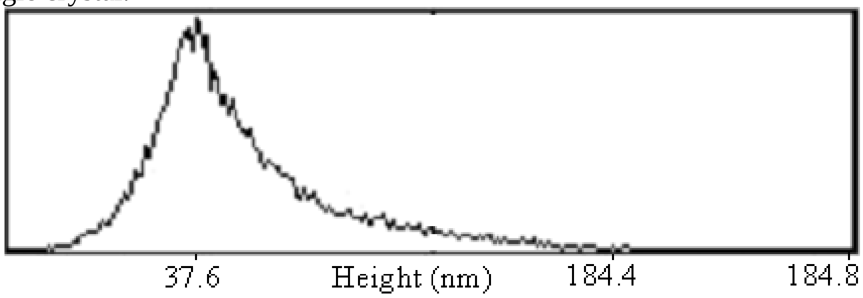

Fig.1. Distribution of formations by height

The distribution of formations by height has the form of a curve with a sharp maximum (Fig. 1) at 37.6 nm. The proportion of formations with sizes less than the most probable is 37%. It is assumed that the modification of nanomorphology is carried out due to self-organization [1, 2]. Process control can be achieved using modern methods of plasma chemical micromachining, which allow modifying the nanomorphology of the surface of crystals, initiating the nucleation of formations of the required size and surface density. Such an approach opens up possibilities for creating quantum-size systems in two- and three-dimensional structures.

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EFFECT OF LOW-TEMPERATURE ION-NITRIDING OF TITANIUM ALLOY (TI-6AL-4V) ON PARAMETERS OF SURFACE LAYER

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Currently, one of the most effective ways to modify the surface of titanium alloys is ion nitriding. However, it is known that ion nitriding is carried out at high temperatures, which in turn leads to an increase in the structural parameters of the material and the deterioration of its mechanical properties [1-3].

Currently, work is underway to study the low-temperature ion nitriding of titanium alloys, which allows us to maintain a high surface finish and eliminate the deterioration of the mechanical properties of the material [3].

This work is devoted to the comparison of two methods for modifying the surface of a titanium alloy Ti-6Al-4V at low temperatures: nitriding in a glow discharge and nitriding in a non-self-sustained high-current arc discharge. The effect of low-temperature ion nitriding of titanium alloy Ti-6Al-4V on the surface microhardness, the depth of the nitrided layer, roughness and surface residual stresses is considered.

As a result of the study of the effect of nitriding temperature, it was found that treatment, both in a non-independent high-current discharge and a glow discharge at a temperature of 450°C, increases the surface microhardness of samples from titanium alloy Ti-6Al-4V by 1.2 times. As the nitriding temperature rises to 600°C, the surface microhardness of samples processed in a glow discharge increases by 1.3 times. Processing in a non-self-directed high-current arc discharge increases the surface microhardness by 1.8 times.

It has been established that the temperature of ion nitriding affects the surface roughness of the samples. So with an increase in temperature from 450 to 600°C, the roughness value of the surface being treated increases by 2 ... 2.5 times.

It is established that the temperature of nitriding affects the sign and the value of residual stresses. So, with ion nitriding in a non-self-sustained high-current arc discharge and in a glow discharge at a temperature of 600°C, the residual voltages were +12.4 and – 8.4 kgf / mm^2, respectively. When nitriding in a non-self-acting high-current arc discharge at a temperature of 450°C, the residual stresses amounted to +0.5 kgf / mm^2, after treatment in a glow discharge - 23.7 kgf / mm^2.

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INFLUENCE OF HYDROGEN CONTENT ON THE PROCESS OF LOW-TEMPERATURE ION NITRIDING TITANIUM ALLOY TI-6AL-4V IN CG AND UFG STATES*

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Currently, one of the most effective methods for hardening the surface of parts made of titanium alloys is ion nitriding [1-3]. It is known that the composition of the gas mixture during ion nitriding significantly impact on the structure, properties, phase composition and growth kinetics of the modified layer. The presence of hydrogen in the nitriding mixture increases the diffusion of nitrogen by removing the nanocrystalline layer on the surface of the titanium alloy, which hinders the process of nitriding [4, 5]. However, there are no data on the effect of the hydrogen content in a three-component gas mixture (nitrogen-argon-hydrogen) with low-temperature ion nitriding of titanium alloys (T≤600° C) on the technological parameters and properties of the modified layer.

In this work, low-temperature ion nitriding of titanium alloy Ti-6AL-4V in a coarse-grained state (CG) was carried out at a temperature of 600° with different hydrogen contents (0-30%H_2). Based on the results obtained on CG samples, nitriding of titanium alloy Ti-6AL-4V in the ultrafine-grained state (UFG) was carried out at a temperature of 550° with a hydrogen content of 0 and 10%. Microhardness measurements were carried out over the depth of the hardened layer, optical and SEM images of the microstructure were obtained after nitriding. Studies of the current-voltage characteristics of the discharge with different hydrogen contents and gas mixture pressure were carried out.

To assess the effect of hydrogen content on the depth of the hardened layer, and as a consequence on the kinetics of its growth, the curves of the distribution of hardness over the depth of the modified layer were obtained (Fig. 1). Analysis of the plot showed that the addition of hydrogen to the gas mixture leads to an increase in the surface microhardness from 460 $HV_{0.05}$ with nitriding without hydrogen, to 530 $HV_{0.05}$ with the addition of 20% hydrogen. A further increase in the hydrogen content to 30% leads to a decrease in the surface microhardness value to values of 460 $HV_{0.05}$.

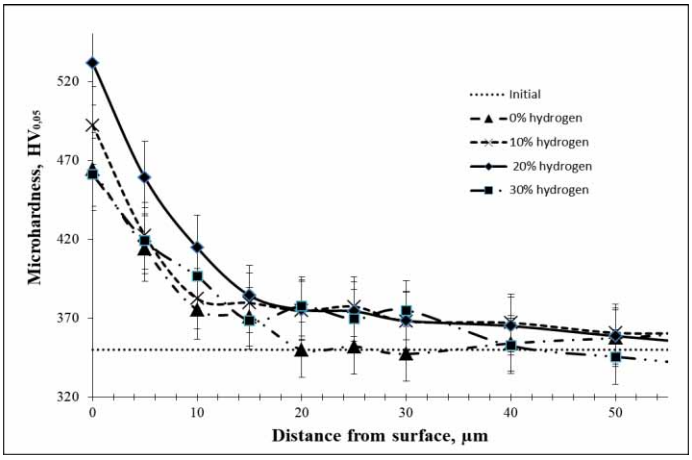

Fig. 1. Plot of microhardness distribution over the depth of the hardened layer

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MODEL CALCULATION OF THE STOICHIOMETRIC COMPOSITION OF THREE-COMPONENT VACUUM ION PLASMA COATINGS*

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A mathematical model of the process of vacuum-arc deposition of coatings of the Ti-Al system in the environment of various gases (nitrogen, oxygen, carbon) has been developed, which allows one to calculate the stoichiometric composition of 3-component coatings. On the basis of the model, a program was created to determine the stoichiometric composition of the coatings depending on the technological regimes (Fig. 1). The samples were deposited with 3 component coatings in the environment of various gases (nitrogen, oxygen, carbon) by calculated regimes (Fig. 2). To determine the adequacy of the mathematical model, the chemical composition of the coatings was determined using energy dispersive analysis. The results of comparing the calculated with the experimental data obtained, it was found that the error of the model is within 10%. The use of the developed model and computer program will allow at the stage of development of the technological process to choose the modes of applying 3 component coatings.

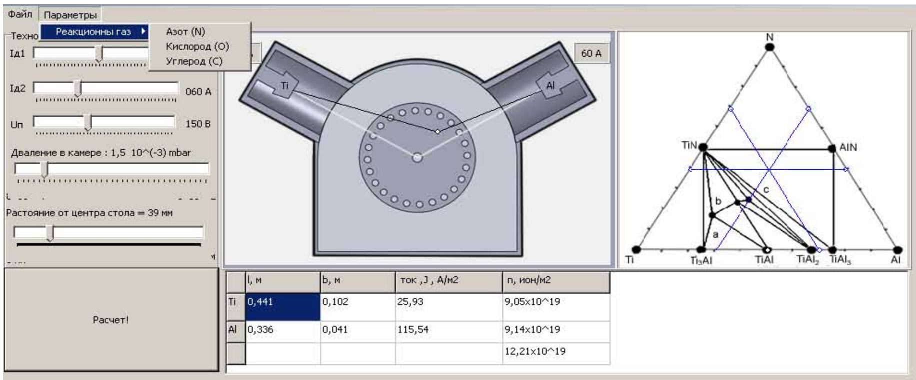

Fig. 1. Interface of the program "Determination of the stoichiometric composition of coatings based on an intermetallic compound Ti-Al system deposited from a vacuum-arc discharge plasma in a medium of various gases"

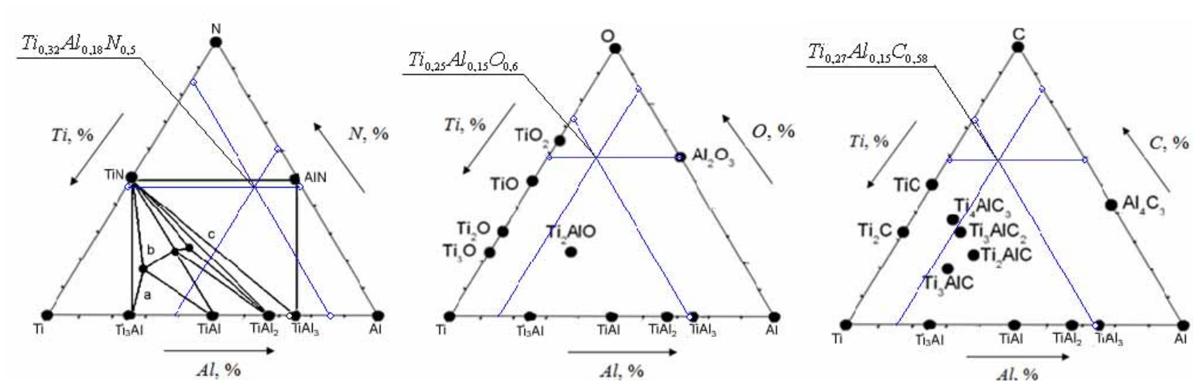

Fig. 2. Interface of the program "Determination of the stoichiometric composition of coatings based on an intermetallic compound Ti-Al system deposited from a vacuum-arc discharge plasma in a medium of various gase

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EFFECT OF VACUUM ARC PLASMA COATINGS DEPOSITION CONDITIONS ON PARTS QUALITY PARAMETERS

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Hard coatings, synthesized by physical vapor deposition (PVD) are widely used as an inexpensive way to increase the service properties dew to their excellent properties. It is highly desirable to deposit a thin coating and increase significantly the service properties. The achievable service properties depend not only from deposited material but from coating structure and surface layer quality. Service properties differ in required values of surface quality parameters for different application. Thus, ensuring the required service properties by controlling the surface quality parameters is highly demand. Therefore, researches aimed at revealing the regularities of surface properties formation under the coating deposition conditions are particularly relevant. Following coating and surface parameters were studied: surface roughness, coating adhesion properties, hardness and wear resistance properties. The following deposition conditions were varied: deposited material, ion source focusing current, substrate negative bias, substrate location and substrate initial condition. Effect of additional ionization sources such as plasma source with filament cathode and plasma source with hollow cathode presence was also studied. The experimental results are highly promising in industrial application through their wide industrial application.

OXIDATIVE PLASMA CHEMICAL TRANSFORMATIONS OF C_3-C_4 ALKANES*

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The results of plasma-chemical transformations of C_3-C_4 alkanes as a liqified petroleum gas (LPG) in a barrier discharge plasma in the presence of octane are presented. The transformations of the components of gas-liquid mixture result in the formation of predominantly hydroxyl and carbonyl compounds with the same number of carbon atoms in a molecule as in the starting compounds. The presence of a octane favours an effective removal of the reaction products from the discharge zone due to dissolution of the compounds formed therein.

The main active particles in a non-thermal plasma of the barrier discharge are alkyl radicals, atomic oxygen, and hydrogen. The formation of both oxygenated compounds and hydrocarbons with isomeric structure occurs as a result of their further chemical transformations. The mechanism of conversion of gaseous hydrocarbons is much like that for the conversion of liquid hydrocarbons in a barrier discharge plasma. They both are carried out under similar conditions.

The changes in the initial concentration of the propane and butane in the initial gas mixture from 10 to 75 % wt result in a decrease in the conversion of gaseous hydrocarbons from 4.1 to 0.9 % wt, while the conversion of octane decreases from 2.4 to 0.3 % wt. in one pass through the reactor. The decrease in hydrocarbon conversion is due to decrease in the rate of formation of atomic oxygen in a discharge gap of the reactor.

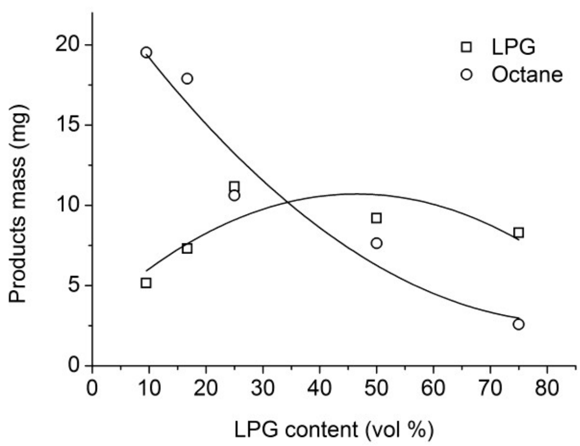

Fig. 1. Mass of the products of the plasma chemical transformation of LPG and octane

Theoretical calculations for the model oxygen-propane mixture have been made using the Bolsig+ software. The results of calculations show that the oxygen dissociation rate constant decreases from $1.87 \cdot 10^{-10}$ cm^3/s to $6.71 \cdot 10^{-9}$ cm^3/s due to a decrease in the mean electron energy from 4.1 to 3.4 eV. It is found out that the mass of products formed in the result of oxidation of gaseous and liquid hydrocarbons depends on the initial concentrations of starting compounds in the vapor-gas mixture. A simple expression is proposed to evaluate the preferential direction of the plasma-chemical reaction depending on the initial concentration of hydrocarbons in a discharge gap of the reactor.

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EFFECT OF ELECTRON-BEAM IRRADIATION ON THE SAFETY AND QUALITY OF HELMINTHOSPORIUM-INFECTED BARLEY

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The fungus Helminthosporium (*Helminthosporium sativum* Pam.) is a widely distributed cereal pathogen, but the disease is most harmful in the eastern regions of Russian Federation [1].

In connection with the ecological orientation of agriculture, at present, the efforts of many scientists are aimed at finding new methods of disinfecting seeds without the use of pesticides.

At the end of the last century, it was shown that presowing irradiation of seeds of agricultural crops can be used to increase crop yields [2].

Previously at a low-energy electron accelerator with a plasma cathode and the beam output into the atmosphere it was shown that presowing irradiation of barley seeds of the Vladimir variety reduces of the development of helminthosporiosis in seedlings [3]. Studies on the presowing of seeds at an electron-beam accelerator in an extended dose range from 1 to 8 kGy and a dose rate of 500 Gy per impulse allowed to establish that the progression of the disease depends on both the radiation dose and the post-radiation period.

The most effective was the effect of irradiation during the post-radiation period of 4 days – a decrease in the degree of damage by 33-48 % was observed at doses of 4-8 kGy, and the prevalence of the disease – by 29-46 % (Fig. 1).

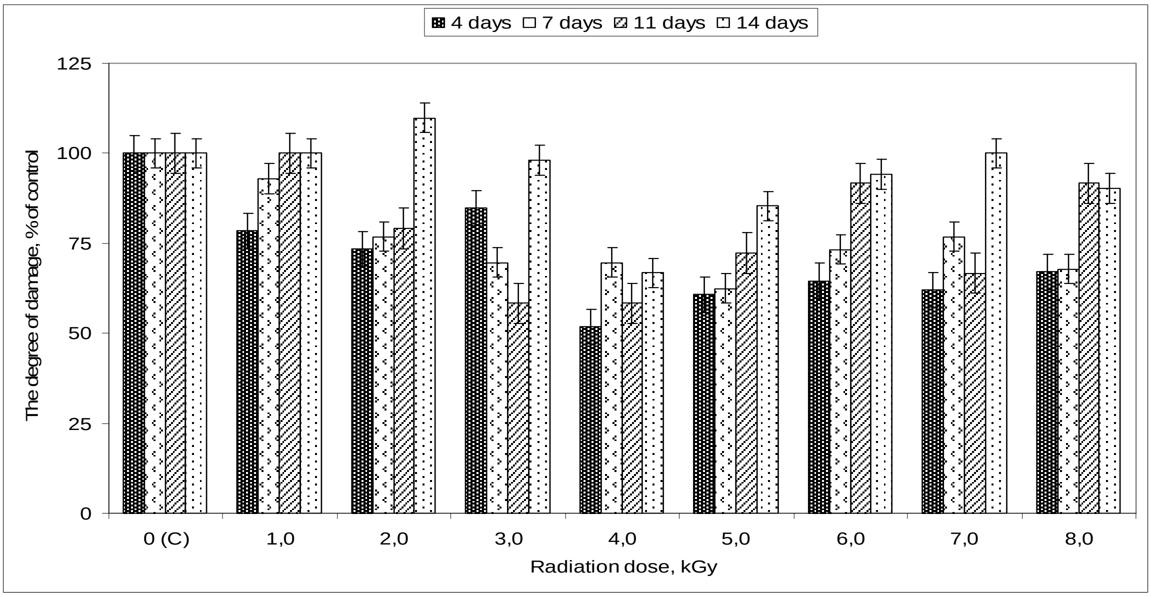

Figure 1. The effect of irradiation on the damage of barley by *Helminthosporium sativum* depending on the post-radiation period

Thus, it was shown that presowing electron-beam irradiation of spring barley of the Vladimir variety reduces the resistance of *Helminthosporium sativum*.

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EFFECT OF TRENCHES ON SHEATH FORMATION NEAR EMISSIVE SURFACE IN LOW PRESSURE PLASMA IN MAGNETIC FIELD*

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The erosion of emissive surfaces during long term operation essentially effects the working characteristics of low temperature plasma devices. The transition in sheath structure near the emissive surface with erosion patterns in low temperature plasma is essentially different for planar and non-planar surfaces [1].

In this work, we study the formation of the plasma sheath near the emissive floating sample with complex topology in magnetic field normal to the sample. From the experimental and calculated data, the spatial potential distribution was derived for a) a sample made from Al2O3 with the trenches and b) for a planar control sample. In Fig. 1, the sketch of the experimental setup is shown. Experimental study was carried out in a vacuum chamber filled with Argon with a pressure of 0.05-0.2 mTorr. The cylindrical chamber 1 is made of stainless steel and is closed with the ends of the covers in a flange manner. The diameter of the test volume of 160 mm. The covers have insulated vacuum electrical inputs for supply the thermal emission cathode 5, make potential between the cathode and the chamber, and measuring signals from Langmuir probes 9. The applied voltage ranges from 30 V to 300 V, the external magnetic field is 20 G. The emissive sample with a complex topology is a disk with trenches with depth and width of 5 mm. The simulations of spatial distribution of plasma parameters were performed with Particle in Cell Monte Carlo Collision method for the experimental conditions. Both the experimental and calculation results show considerable difference in the sheath structure transition with increasing the applied voltage for planar and non-planar cases.

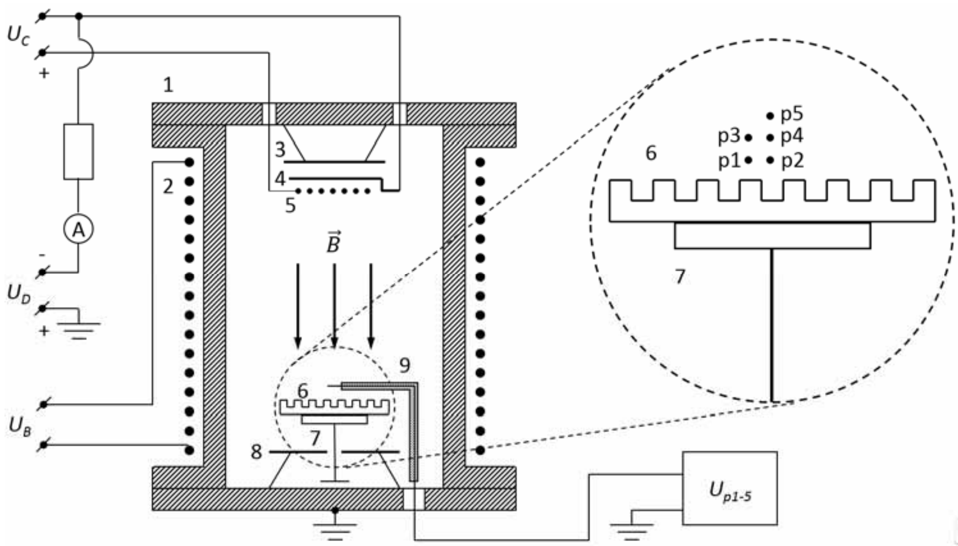

Fig. 1. Work chamber scheme: 1 – vacuum chamber, 2 – magnet system, 3 – screen, 4 – cathode screen, 5 – thermionic cathode, 6 – sample, 7 – foot plate, 8 – screen, 9 – Langmuir probe.

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PARTICLE GENERATION DURING LASER-PLASMA TREATING OF METALS IN EXTERNAL ELECTRIC FIELD

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The radiation of the GOR-100M ruby laser operating in the free oscillation regime (pulse duration ~1.2 mc) passed through the focusing system and was directed through the hole in the electrode onto the sample that served as the second electrode and was mounted in air at a pressure of 10^5 Pa. The energy of the laser pulses varied from 5 to 60 J. The voltage was applied to the electrodes from the source, built on the basis of the UN 9/27-13 voltage multiplier of the TVS-110 unit. The source allowed the voltage variation within 25 kV and its stabilization in the course of the experiment. To study the spatial and temporal evolution of the laser plasma torch in the course of laser radiation action on the sample, we used the method of high-speed holographic motion-picture recording. Presence of an external electric field weakly affects the concentration of electrons in the laser plasma plume. When either positive or negative potential is applied to the sample, many small droplets appear on its surface after the laser action. In particular, at the laser pulse energy 20 J, the diameter of the focusing spot 2 mm, and the electric field strength 10^6 V/cm we observed ejection of droplets having the mean characteristic size less than 0.1 mm to the distance up to 2 cm from the crater centrum. The maximal characteristic size of drops was ~ 0.4 mm. In the absence of the external electric field the mean size of the droplets was ~ 0.4 mm. The droplets were seen at the distance up to ~ 1 cm from the crater centrum. The primary plasma formation and the initial stage of the laser plume development, in principle, do not differ from those observed in the absence of the external electric field. The metal is melted and evaporated. As a result of local formation of steam and plasma, the erosion plume begins to form with the fine-dispersed liquid-drop phase. Note, that the bulk evaporation is promoted by the gases, diluted in the metal, and by the spatiotemporal non-uniformity of the laser radiation. At a radiation flux density 10^6 – 10^7 W/cm^2 the bulk evaporation is typical of all metals used in the experiments. Obviously, the presence of the external electric field affects (increases or decreases depending on the direction of the field strength vector) the velocity of motion of the plasma front and causes some distortion of the plasma cloud shape. It is essential that the mentioned differences (at the considered parameters of laser radiation) are observed only at the initial stage of the laser plume development, because after the steam-plasma cloud reaches the electrode an electric breakdown (short-circuit) occurs, and the external field in the interelectrode gap disappears. The significant difference in the characteristic size of droplets, observed on the surface of the irradiated sample in the presence of the external electric field (independent of the direction of the field strength vector) and in the absence of the field, is a manifestation of the following mechanism of droplet formation. It is known that at the surface of a liquid (including a liquid metal) the formation of gravity-capillary waves is possible under the action of various perturbations. Undoubtedly, the examples of such perturbations are the spatially non-uniform evaporation of the target material due to non-uniform heating caused by non-uniform energy distribution over the focusing spot, the non-uniform primary plasma formation caused by roughness of the irradiated sample surface, and, in the first place, the slop of the molten metal initiated by each spike of laser radiation, acting on the exposed sample.

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