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INSTITUTE OF ELECTROPHYSICS UB RAS

Institute of High Current Electronics SB RAS

ABSTRACTS

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Institute of Electrophysics UB RAS

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The GDPA Conference is a platform for researchers to discuss a wide range of scientific, engineering and technical problems in the areas of fundamental low temperature plasma processes: low and high pressure discharges, near-electrode phenomena, ultrafast processes, diagnostics radiation, ultrafast processes, diagnostics; gas discharge methods for surface modification and deposition of coatings: surface modification, ion implantation, combined surface treatment methods; plasma chemical, electrophysical and laser technologies: environmental applications, production of laser technologies: environmental applications, production of nanopowders and functional materials; low temperature plasma sources: continuous, pulsed and pulsed generators, gas switches, power supply.

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Конференция «Gas Discharge Plasmas and Their Applications» уже стала традиционной для специалистов в области физики плазмы и ее применения.

Наша миссия состоит в организации площадки взаимодействия, обмена опытом и создания новых коллективов для ученых разных научных школ физики плазмы. Мы бы хотели сохранить лучшие традиции предыдущих конгрессов GDP и EFRE и обеспечить делегатам множество возможностей для участия в дискуссиях, создания новых и укрепления существующих партнерских отношений и сотрудничества в России и за ее пределами.

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Для нашего университета большая честь стать площадкой для проведения такой знаковой Конференции, и мы с радостью будем ждать вас у себя в гостях!

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науки и технологий,
докт. хим. наук, проф.

В.П. Захаров

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GENERATION OF LOW-TEMPERATURE PLASMA IN LOW-PRESSURE VOLUME DISCHARGE AND ITS APPLICATIONS

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The electrode systems and main power supply parameters for initiating and maintaining low-pressure glow and arc discharges are considered, in which volume low-temperature plasma is efficiently generated both for its direct use in scientific and technological purposes, and as a working medium for extracting charged particles, which after acceleration are able to modify the surface of materials and products in order to give it improved physical and mechanical, functional and operational properties.

The integrated electrophysical installations developed and created at the IHCE SB RAS based on the studied low-pressure discharges provide a set of parameters that differ from the known ones, which makes it possible to implement such complex processes as:

- final ion-plasma cleaning and activation of the surface of materials and products using plasma of inert gases;
- ion-plasma nitriding in the plasma of volumetric arc and glow non-self-sustaining low-pressure discharges;
- electric arc and magnetron plasma-assisted deposition of functional coatings;
- electron-beam modification of layers and coatings using large-section beams generated by electron sources with a grid plasma cathode based on low-pressure volume discharges.

The main parameters and technological capabilities of such ion-plasma installations modernized or newly created in recent years as "KVINTA", "ELION", as well as the complex electron-ion-plasma installation "COMPLEX" are given. Examples of implemented processes for modifying the surface of materials and products are given, which made it possible to significantly improve their physical and mechanical properties, and their operational properties, which ultimately leads to an increase in their service life.

The results of the research and development carried out are used in the creation and operation of a vacuum electron-ion-plasma stand designed for in-situ studies of surface modification of materials and products using synchrotron radiation.

This work was carried out with the financial support of the Russian Federation represented by the Ministry of Science and Higher Education (project No 075-15-2021-1348) within the framework of event No. 3.2.6.

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SCIENTIFIC RESEARCHES AND PRACTICAL DEVELOPMENTS OF THE INSTITUTE OF ELECTROPHYSICS UB RAS

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The Institute of Electrophysics of the Ural Branch of the Russian Academy of Sciences was founded by Academician G.A. Mesyats in 1986 with the aim of developing a new field of physical research, namely, pulsed power technology in the Ural region. Today, the scientific activity of the Institute is focused on the following topics: physics and engineering of high energy densities, generation and application of plasma and charged particle beams, nanotechnologies, sources of coherent radiation, new optical media and nonlinear optics, theory of strongly correlated systems. Pulse power devices developed at the Institute are designed for research in the area of strong electric and magnetic fields, powerful electron and ion beams, and extremely fast pulsed phenomena. Therefore, they are, first, unique tools for fundamental physics. At the same time, many years of research experience, engineering achievements and cooperation with other institutes allow the institute's developers to offer pilot devices for implementation in high-tech industries, agriculture, and medicine.

The report will consider a number of scientific results of the Institute of Electrophysics of the Ural Branch of the Russian Academy of Sciences, which have both fundamental and applied significance.

ULTRAFINE GRAINED MATERIALS WITH ION-PLASMA SURFACE MODIFICATION - POTENTIAL FOR INNOVATIONS*

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Ultra-fine grained (UFG) metallic materials with grain size in the nanometer range processed by severe plastic deformation (SPD) techniques have been of particular interest in recent years [1,2]. Such UFG materials have very high strength due to the fine grain size and high density of nonequilibrium grain boundaries [3].

However, along with strength, corrosion and erosion resistances of products determined by the surface properties are important characteristics of materials for their structural applications. Therefore, surface modification by ion implantation, ion nitriding [4], deposition of coatings [5,6], etc. are widely used to improve the performance characteristics of material surfaces.

This report is focused on the promising results on the recent studies of UFG materials (Al and Ti alloys, steels) with ion-plasma modification of the surface. These studies demonstrate a significant additional increase in the service properties of such materials - erosion resistance, strength and fatigue. The physical nature of these advanced properties is discussed and examples of innovative applications are considered.

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G1-O-000301

ELECTRON BEAM PLASMA GENERATION AT THE FOREVACUUM PRESSURE RANGE

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A review of recent results of experimental studies and numerical simulation of the special features of the formation processes, parameters and characteristics of low-temperature beam plasma in the forevacuum pressure (units-tens of Pa) is presented. The attractiveness of beam plasma at such pressure range is due to its influence on the processes of electron beam charge neutralization of an electrically non-conductive surface. This opens up the possibility of direct electron-beam modification of dielectric materials. To obtain an electron beam with an energy of several keV in this pressure range, a so-called forevacuum plasma source of electrons was used. An electron source based on a glow discharge with a hollow cathode provided the generation of a focused continuous electron beam, while a cathode arc was used to generate a high-current wide-aperture pulsed electron beam. The parameters of the beam plasma and their dependence on the beam current, the energy of accelerated electrons, as well as the pressure and type of the working gas are measured. The conditions for initiation in the transport region of instability of the "beam-plasma discharge" type are determined. The role and degree of influence of secondary electrons and thermionic emission from the surface of an electron collector on the processes of beam plasma generation are determined. The features of beam plasma generation during the transport of an electron beam in an extended narrow metal tube are also studied. The results of numerical simulation are in satisfactory agreement with experiment. This gives better understanding of the main physical mechanisms of beam plasma generation in higher pressures of the forevacuum range.

The research is supported within the framework of the state task of the Ministry of Education and Science of the Russian Federation project FEWM-2023-0012.

G1-O-000901

VOLUME DISCHARGES AT SUPERATMOSPHERIC PRESSURE IN CO_2–LASER MIXTURES WITH HIGH PUMPING ENERGY DENSITY

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The transition from atmospheric pressure to superatmospheric in TE–CO_2 lasers ensures the achievement of higher values of radiation energy per pulse at a shorter duration.

Successful implementation of spatially homogeneous volumetric pumping discharges at superatmospheric pressures is possible if a sufficiently high level of initial ionization of the working gases in the interelectrode gap is ensured. Efficient absorption of ionizing VUV radiation by carbon dioxide molecules requires a maximum reduction in the distance between the source of initial ionization and the gap for ignition of a volume discharge.

The problem of increasing the intensity of the source of ionizing VUV radiation and its location very close to the main gap was solved by using a three-electrode structure with successive ignition of an auxiliary preionization corona discharge and a volume discharge. The main discharge gap was formed by a monolithic profiled graphite electrode and a flat grid electrode. The volume of the excited plasma in this gap was V = 7.5x0.8x0.8 cm = 4.8 cm^3. The auxiliary electrode in the form of two strips of molybdenum was located above the grid electrode. The value of this gap was 0.4 cm. A high-voltage pulse was applied to the contacts of the auxiliary electrode and cathode of the main gap. At the initial moment, an auxiliary high-current corona discharge is ignited and illuminates the main gap through the grid anode. This process continues during the charging time of the "anode-cathode" constructive capacitance. After that, a breakdown of the main gap occurs with the current flowing through both gaps connected in series.

During the research typical gas mixtures CO_2:N_2:He were used in the ratios 1:1:2 (1), 1:1:3 (2), and 1:1:6 (3).

As a result of this work, the following new data were obtained:

1. The pumping energy increases linearly with pressure within 1–5 atmosphere and at pressures of 5 and 6 atmosphere for a mixture CO_2:N_2:He = 1:1:2 is 4.5 J.

2. The maximum values of the pumping energy density are typical for a pressure of one atmosphere and are, respectively, for mixtures 1:1:2 – 400, 1:1:3 – 320 and 1:1:6 – 200 $mJ\cdot cm^{-3}\cdot Atm^{-1}$. As the pressure increases to 6 atmospheres, the pumping energy density decreases to 150, 140, and 100 $mJ\cdot cm^{-3}\cdot Atm^{-1}$, respectively.

DEVELOPMENT OF NANOSECOND DISCHARGE IN AN INHOMOGENEOUS ELECTRIC FIELD IN WATER MEDIUM

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For many years, electric discharge technologies have been considered by researchers as a means for purifying aqueous solutions from various pollutants [1, 2]. In particular, due to the presence of unique properties, one of the most promising methods is a nanosecond high-voltage discharge, under the conditions of ignition of which a highly nonequilibrium low-temperature plasma enriched with a large amount of chemically active is formed [3]. Despite the fact that there are many works devoted to the purification of water by a short-pulse discharge, there are still many questions regarding the formation of this type of discharge.

The development of nanosecond discharge in distilled water has been studied with fast-framing devices. Positive and negative nanosecond voltage pulses with amplitudes of 50 and -60 kV were applied either across a 2-mm point-to-plane or point-to-point gaps located in a quartz cuvette filled with distilled water (Fig.1). Pointed electrodes were made of pieces of sewing needles. The discharge chamber had a capacitive voltage divider and a current shunt made of SMD resistors. Time-resolved images of optical emission of discharge were taken with a four-channel ICCD camera with a minimal exposure duration of 3 ns. It allowed taking three consecutive and one time-integrated images per one pulse with simultaneously recording voltage and current waveforms. It was observed that discharge was initiated when the pointed electrode was positive. One or several streamers appeared on the surface of the positive needle and then they branched forming a semblance of a crown that occupied a large region near the needle. It looked like a quasi-volume discharge. A spark channel was formed as soon as one or two streamers (branches) reached the opposite electrode. In the point-to-point gap, the discharge was also initiated near the positive needle. However due to the alternation of polarity of reflected nanosecond voltage pulses, the formation of streamers occurred near both needles. The collision of streamers was observed in the middle of the gap. A bright light flash accompanies the collision. In the place where the streamers collided, there was a long afterglow.

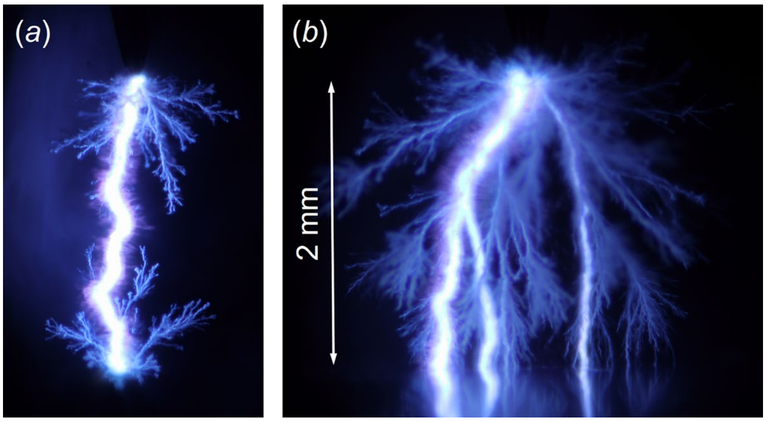

Fig. 1. Integral images of the plasma glow at an electrical discharge in distilled water. *a*) point-to-point gap; *b*) point-to-plane gap.

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G1-O-001802

METHODS FOR STABILIZING THE ELECTRON BEAM CURRENT IN SOURCES WITH A PLASMA CATHODE AND ANODE

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Electron sources with plasma cathodes are widely used in science and technology [1]. Such sources, regardless of the type of discharge used to generate emission plasma in the plasma cathode, use beam current stabilization systems. In the case of continuous electron sources, the stabilization system makes it possible to achieve the ripple factor of beam current at the level of a few percent. But when switching to pulsed beams with a pulse duration of the order of hundreds of microseconds or even less, the beam current stabilization system is a separate complex technical solution, since it must have the maximum possible depth of the feedback loop and work out instabilities in a time much shorter than the duration of the beam current pulse, i.e. provide a feedback frequency of the order of 1 MHz, which can be very difficult and expensive solution. Stabilization of the beam current for pulsed sources is especially important when it comes to controlling the beam power to form the required temperature field in the surface of the workpiece, for example, when generating modulated electron beams [2, 3].

In this paper, we consider methods for introducing self-consistent feedback in an electron source [4] with a plasma cathode based on a low-pressure arc discharge with grid stabilization of the emission plasma boundary and a plasma anode with an open plasma boundary to stabilize the electron beam current along the ion flow from the anode plasma into plasma cathode space. The anode plasma in such a system is produced by the electron beam itself, so its concentration depends on the conditions of its generation (accelerating voltage, beam current density, gas pressure, magnetic field strength, etc.). In this case, the main destabilizing factor is the change in these generation conditions during a submillisecond beam current pulse.

The issue of beam current stabilization in the system of such a source with grid control of its amplitude is considered separately. Methods for increasing the depth of feedback through the use of operational amplifiers are proposed.

It is shown that the use of negative feedback in such systems with respect to the ion flux into the plasma emitter from the accelerating gap makes it possible to ensure the reproducibility of generation modes and the repeatability of the processes of beam action on the surface of metallic materials.

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NUMERICAL AND PROBE STUDIES OF FAST ELECTRONS KINETICS AND PLASMA PARAMETERS OF A SHORT GLOW DISCHARGE IN HELIUM AND NEON

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An urgent problem of modern gas-discharge plasma physics, both from the fundamental point of view and from the point of view of applied possibilities, is the study of near-cathode glow discharge (GD) plasma in a wide pressure range. As is known, two plasmas differing in their properties are generated in GD: near-cathode plasma, which includes negative glow plasma (NG) and Faraday dark space (FDS) and positive column plasma (PC) [1,2]. Compared to PC, NG-like plasma has been neglected for a long time [1,2]. Despite this, for low-pressure discharges, it was found that the plasma in the NG is formed by a beam of fast electrons that has accumulated its energy in the cathode layer and, thus, the ionization source is nonlocal [1, 2]. In this case, the temperature of the main group of electrons, in contrast to the PC plasma, is low and amounts to tenths of 1 eV. In addition, the electron distribution function (EDF) in the NG plasma is nonlocal. These features opened up the possibility of identifying impurities in the buffer helium in the plasma of the NG of a short GD by recording the spectra of fast electrons that appeared in Penning ionization (PI) reactions.

The aim of the presented work was to carry out numerical and experimental studies of the short GD plasma at low and high pressures. To this end, a self-consistent hybrid model of short GD in helium and neon was formulated. It is based on the Boltzmann kinetic equation, the written two-term Lorentzian approximation, the fluid description of the heavy plasma component, the Poisson equation and the heat equation. Elementary processes took into account the formation of singlet and triplet states of the helium (or neon) atom, the metastable level of molecular helium (or neon), and the atomic and molecular helium (or neon) ions. The set of plasma-chemical reactions was compiled from works [3,4]. On the basis of the formulated model, numerical calculations were carried out at pressures from 300 Pa to 100 kPa. The results demonstrated the experimentally observed pattern in the distribution of NG plasma parameters. On the isotropic and anisotropic parts of the EDF, the formation of narrow peaks from characteristic electrons produced as a result of PI impurities of atomic and molecular gases (Ar, N_2, O_2, and CO_2), hydrocarbons (CH_4 and C_2H_5OH), their derivatives, and metastable helium atoms was shown. Numerical analysis made it possible to determine the sensitivity of the method for detecting impurities in NG plasma. It was one hundred thousandth, which corresponds to modern mass spectrometric methods. Verification of the simulation results with the results of calculations using the PIC/MCC model [3] and validation of the model with our own probe studies showed good quantitative agreement.

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SIMULATION OF DYNAMICS AND FAST HEATING OF GAS OF MICROWAVE DISCHARGES IN NITROGEN AND AIR

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Focused and freely localized microwave discharges are widely used in the aerospace industry. In particular, they are used in problems of reducing power and heat loads on high-speed aircraft, in modeling the entry of spacecraft into planetary atmospheres, in studying gas flows in high-enthalpy installations, and in studying combustion processes.

The paper presents the results of numerical calculations on plasma dynamics in a microwave discharge in nitrogen and air under the experimental conditions from [1].

The model was based on the balance equations for charged and excited particles, the balance equations for the energy of electrons and the heavy plasma component, and the system of Maxwell equations for describing the microwave electromagnetic field [3]. To describe the microwave discharge in nitrogen, a set of reactions from [2] was considered. To describe the microwave discharge in air, a set of reactions from [4, 5] was considered.

In addition, the model took into account the balance equation for the vibrational energy of nitrogen, and the kinetics of elementary processes included the mechanisms of rapid gas heating [2] and vibrational-translational relaxation. The rates of inelastic processes with the participation of electrons were determined using the Maxwellian EDF and the EDF obtained in the framework of the local Boltzmann kinetic equation.

As a result, the dynamics of the breakdown of the microwave discharge and its elongation along the oscillating electric field is presented. A transition from a diffuse to a contracted (filamentous) form of a microwave discharge is demonstrated. Quantitative agreement was shown in gas temperature and electron density with experimental data at times longer than 7 μs [3]. The influence of a small admixture of oxygen leads to agreement with experiments over a larger interval of the studied times. It should be noted that the results obtained using the Maxwellian EEDF are in better agreement with the experimental data at short discharge development times.

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FEATURES OF THE PLASMA JET FORMATION IN LOW-CURRENT COAXIAL PLASMATRON WITH A POSITIVE POLARITY OF POTENTIAL ELECTRODE IN ARGON AND AIR *

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Nowadays, plasma jets formed at the basis of the atmospheric-pressure discharges are attracting increasable attention [1, 2, 4]. One of the examples of the systems used for obtaining discharge in a gas flow and plasma jet is so-called non-steady state low-current coaxial plasmatron [1, 3, 6]. In the case, when the gas flow passes through the plasma area, a weakly luminous region, which is often referred to as a plasma jet [2, 3, 6], forms at the exit of electrode system. The jet contains the chemically active particles [3, 6] due to which a great variety of the applications can be provided [1, 2].

Schematic of the plasmatron design and electric circuits for the discharge powering and jet diagnostics are shown in fig. 1.

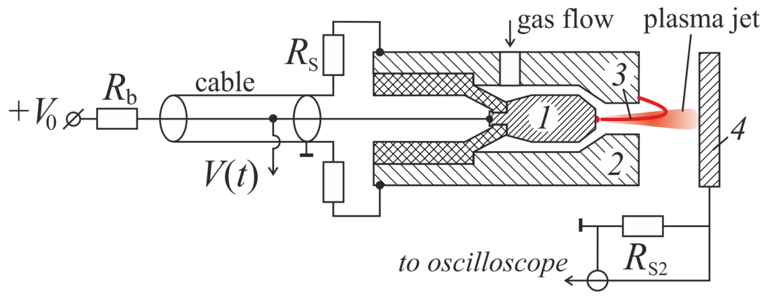

Fig.1. Schematic of the plasmatron design and electric circuits for the discharge powering and jet diagnostics. *1* – anode, *2* – cathode, *3* – gas discharge channel, *4* – additional electrode for plasma jet diagnostics, $V(t)$ – discharge burning voltage, V_0 – power supply voltage, R_b – ballast resistor, R_S, R_{S2} – shunt resistors for current measurement.

The discharge is powered by means of dc power supply with a maximum voltage V_0 up to 5 kV. The power supply is connected to the inner electrode of the plasmatron via the ballast resistor R_b and the coaxial cable whose capacitance is 300 pF. Internal potential electrode *1* and grounded nozzle *2* form the interelectrode gap. For typical operation electric circuits voltage V_0 is negative and electrode *1* is the cathode. In this case current through the jet to the diagnostic electrode *4* is carried mainly by electrons [1, 3, 6].

In this report the results of a study of the features of discharge sustainment and the formation of a plasma jet for the case when the internal electrode *1* is under a positive potential are presented. Waveforms of discharge current and current through the plasma jet using the special diagnostic electrode *4* are obtained. The gas temperature in the plasma jet is measured using thermocouple. Comparison of the features of discharge behavior and jet parameters in argon and in the airflow is carried out. It is shown that due to potential difference between discharge column and grounded electrode *4* ion drift through the jet appears. Ion density in jet was estimated at a level of 10^9 cm^{-3} for the discharge in air and 10^{10} cm^{-3} for the discharge in argon.

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* The work was supported by Russian Science Foundation, project № 22-29-00703.

MECHANISM OF TRIGGERING FOR THE PSEUDOSPARK SWITH WITH A TRIGGER UNIT BASED ON SURFACE DISCHARGE*

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The pseudospark switch is the high current switching device that depends on a pulsed low-pressure gas discharge with hollow cathode [1–3]. This paper presents the data on investigation of one of the methods for the switch triggering. The working gas in the switch is hydrogen whose pressure is maintained in a range of (0.3–0.7) Torr. The anode voltage V_0 = (5–20) kV.

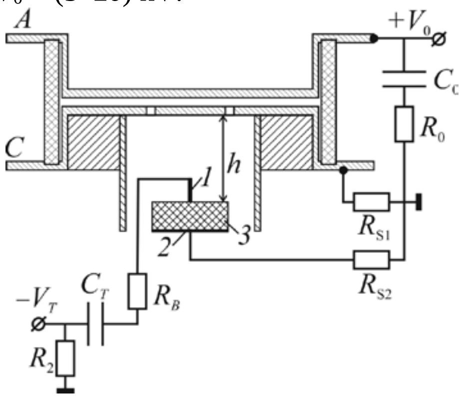

Fig.1. Schematic of the switch and the electric circuit illustrating the method of triggering.

The main high-voltage gap of the switch consists of the anode *A* and the hollow cathode *C*. The trigger unit is located inside the cavity *C* with an inner diameter of 35 mm. This unit comprises of the point electrode *1*, the plate electrode *2* and the dielectric cylinder *3*. The cylinder *3* is made of the ceramic capacitor 470 pF from which the upper plate is removed.

As noted earlier [2, 3], the general principle of any method of the switch triggering is based on generation of plasma in the cavity *C* at a prescribed instant of time. Since the cavity *C* communicates with the main gap via the aperture, the electrons are extracted from this plasma into the main gap, and due to gas ionization, the main high-current discharge is initiated. In the switch with the described trigger system, the mechanism of the plasma generation in the cavity *C* is reduced to the following.

The trigger pulse of negative polarity with a voltage V_T = (2.5–3) kV and the voltage rise time of about 30 ns arrives to the point electrode *3*. Then the pulsed trigger discharge arises over the surface of the ceramic cylinder. In an initial stage of the discharge development, the current of the trigger discharge flows as the displacement current to the opposite plate electrode *2*. The evidence of this current is the signal from the current shunt R_{S2}.

At the next temporal stage, the current to the cavity *C*, that is the current via the shunt R_{S1}, appears. This current increases with time while the current to the electrode *2* starts decreasing. In other words, the trigger discharge is intercepted to the cavity *C*. The positive column plasma forms in the cavity, which leads to the switch triggering.

As a whole, this method offers a possibility to obtain the nanosecond stability of the switch triggering. Depending on the external conditions, the typical delay time to triggering falls in a range of (30–40) ns, and the jitter in the triggering does not exceed 3 ns.

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COMPARATIVE ANALYSIS OF CRATERS FORMED ON CATHODE AND ANODE SPOTS OF A SPARK DISCHARGE IN AIR ON IRON ELECTRODES

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This work continues the study of the technology for obtaining nanopowders by the spark discharge method, carried out at the Institute of Electrophysics, Ural Branch, Russian Academy of Sciences [1, 2]. In order to study the nature of electrode erosion, experiments were carried out to obtain discharge spots on a flat polished surface of an electrode made of St3 steel after single pulsed discharges in an air atmosphere at normal pressure.

The experiments were carried out on a setup for obtaining nanopowders. Control discharges were carried out in an oscillatory mode (OM), corresponding to the usual conditions for the production of powders. Discharge circuit parameters are: capacitance 0.1 μF, current period 1.6 μs, damping factor 1.45. With a charging voltage of 10 to 19 kV, the stored energy of the capacitor was 5, 8.5, 13 and 18 J.

To compare the nature of anode and cathode erosion, discharges with a unipolar mode (UM) of the current pulse were also carried out. To do this, a graphite resistor with a critical resistance was included in the discharge circuit. The stored energy was the same as above, but the charge flowing through electrode was much smaller.

The spots were studied using a surface analyzer (interference microscope) NewView 5010 (Zygo Corp., USA). The research technology is similar to that described in [3]. For each spot, 4-6 shots were taken. The technique for processing microscope data is described in [4]. The relief of the discharge spot is a system of craters surrounded by ramparts. As a result of processing, the sizes, areas and depths of craters are determined.

In the optical microscope images, the trace from the oscillatory discharge had the form of an almost round spot 1.2–1.7 mm in diameter, surrounded by a few of small spots 100–150 μm in size. The area of the discharge spot depends almost linearly on the stored energy.

In all images, the equivalent diameters of the craters were measured (this is the diameter of a circle whose area is equal to the area of the crater). The number of craters in the sample ranged from 80 to 550. The diameters of the craters have a fairly wide distribution, close to log-normal. The minimum diameter was 9–10 μm. The maximum diameters depended on the discharge mode and amounted to 50–70 μm for UM and 130 μm for OM.

Directly from the images of the interference microscope, we also obtained the characteristics of the vertical displacements of the spot topography, such as height ranges, standard deviations of the heights (rms), crater depths, and ridge heights.

The samples of crater diameters (rather, their logarithms) were subjected to a statistical test for the significance of the difference between the variances and average values and for the significance of their dependence on the influencing factors – the discharge energy and the experimental mode. The last factor had levels: cathode, anode and OM. The verification was carried out within the procedures of pairwise comparison of samples and analysis of variance (one-factor and two-factor) in the Excel package. The following results were obtained.

The average values of the diameters are significantly different (but weakly) depending on the spot number (discharge energy). They increase more strongly in the order cathode–anode– OM.

The maximum heights ranges, root-mean-square heights and depths of craters in the UM are somewhat larger for the anode than for the cathode. As for OM, these values are 4-5 times greater than for UM.

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APPLICATION OF LASER RADIATION FOR CONTROL OF RADAN COMPACT PULSE GENERATOR

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The RADAN compact pulse generators have a wide range of practical applications, and increasing the stability of their operation is an important practical task. Commonly used an uncontrolled gas spark gap operating in the self-breakdown mode gives operation stability of 100 – 200 ns [1]. If a laser-controlled spark gap is used, one can obtain a nanosecond turn-on accuracy [2]. However, very accurate synchronization could be obtained using a spark gap controlled by an electron beam [3]. This approach, for some reason, limits the applicability of this technique. The characteristics of laser-controlled switches are determined mainly by the processes of formation and development of laser-induced plasma located in an inhomogeneous electric field. During such plasma generation, even without an external electric field, in some cases, the appearance of instability of its front was observed [4]. Estimates show the model proposed in [5] does not describe these fluctuations, as well as the observed instability in the nano- and subnanosecond range [6]. Under these conditions, the substance can be near and even the supercritical region [7]. In this state, it is characterized by strong density fluctuations, which affect the optical properties of the substance. The latter can lead to an undesirable increase in the instability of such switches. This paper presents an experimental setup and the results of an experimental study of the stability of the operation of an optically controlled spark gap depending on the parameters of the switching process.

This work was financially supported by the Russian Science Foundation and the Government of the Sverdlovsk Region, project no. 22-29-20058.

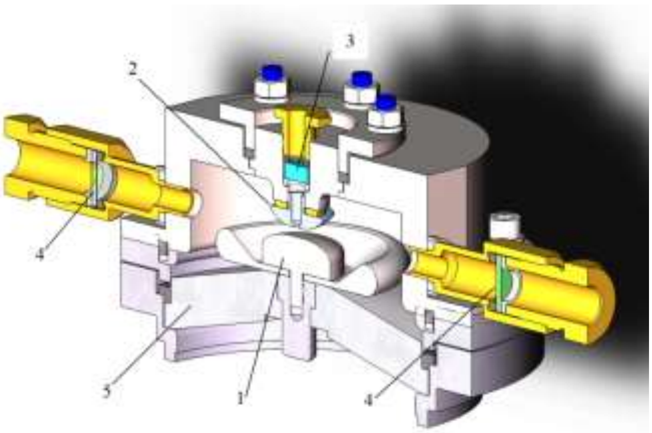

Fig.1. Experimental setup. 1 – anode, 2 – cathode, 3, 4 – windows, 5 – insulator.

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ELECTRON BEAM GENERATION IN ABNORMAL GLOW DISCHARGE UNDER PURE CONDITIONS*

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Earlier in [1] investigations of current-voltage characteristics (IVC) of abnormal glow discharge (AGD) of direct current in pure conditions (achievable vacuum ~10^{-5} Torr) with Ti cathode were conducted resulting in an unusual S-shaped IVCs (in coordinates $U(I)$). The purpose of this work is to continue the study of the peculiarities of electron beam generation and the behavior of the IVC in the AGD with silicon carbide cathode in the system with the achievable vacuum in the discharge cell better than 10^{-6} Torr.

The experimentally obtained IVCs is well approximated by the expression $j = A \cdot U^x \cdot p^y$ [2,3], where j – discharge current density (A/cm²), U – applied voltage (V), p – gas pressure (Torr), A – constant, x and y – degree indices. In [4] the approximation agrees well with the experimental results with the coefficients $A = 2.5 \cdot 10^{-12}$, $x = 3$, $y = 2$. Fig. 1a shows a series of dependences of applied voltage U on reduced discharge current density j/p^2 for discharge in helium under conditions of molecular gas impurity in the working gas not more than 10^{-5}%. Fig. 1a demonstrates: 1 – no coincidence of dependencies for pressure in the range 1.4 – 10 Torr; 2 – the depth of current drop increases with increasing gas pressure; 3 – change in the y value in the range from 2.5 to 1.4 with increasing pressure.

The energy characteristics of the electron beam in the AGD cell were investigated using the calorimetric method, Fig. 1b (curves 1-4). In comparison with the results obtained in [5] with LaB_6 (Fig. 1b (curves 5-7)) and $Mo–Al_2O_3$ (Fig. 1b (curves 8,9)) cathodes, electron beam generation efficiency ~65% (curves 1,2, $U = 2750$ V) is achieved at lower voltages, shorter discharge gap lengths, and higher pressures.

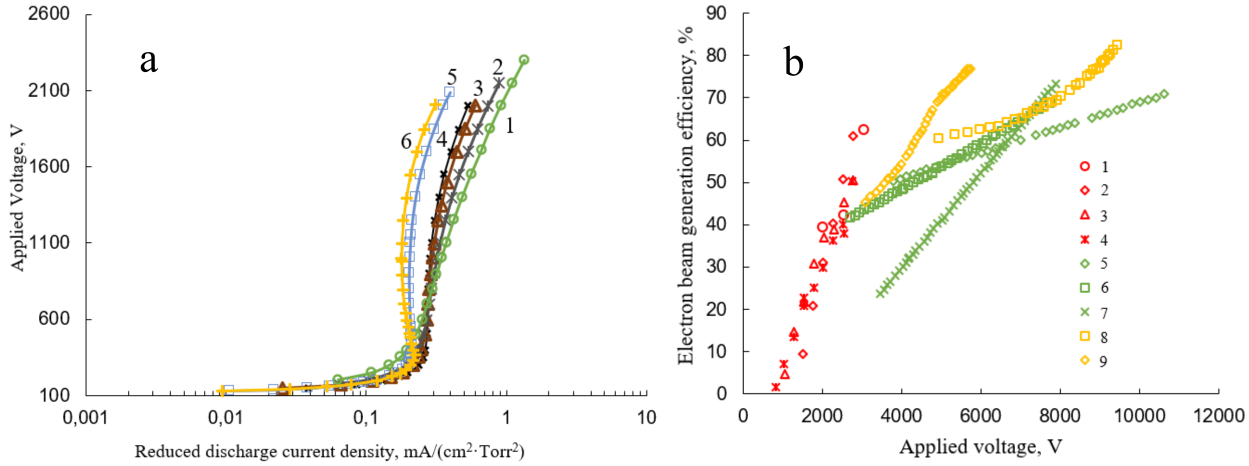

Fig.1. (a) Dependence of reduced discharge current density on applied voltage for different helium pressure p_{He} = 1.4 (1), 2.17 (2), 3.3 (3), 4.3 (4), 6.9 (5), 10 (6) Torr; (b) dependence of electron beam generation efficiency on applied voltage (present work (l (discharge length) = 30 mm, d (cathode area) = 2 cm²): $p_{He} \cdot l$ = 78 (1), 140 (2), 228 (3), 300 (4) Torr·mm; [5] (l = 130 mm, d = 7.41 cm²): LaB_6 cathode, $p_{He} \cdot l$ = 130 (5), 260 (6), 390 (7) Torr·mm; $Mo\text{-}Al_2O_3$ cathode, $p_{He} \cdot l$ = 130 (8), 260 (9) Torr·mm

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INVESTIGATION OF W-FUZZ CATHODE VACUUM ARCS OPERATION TIME*

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The unipolar arc discharge in the thermonuclear facilities with magnetic plasma confinement is an important phenomenon that affects the stability of the plasma pinch. The results are contamination of thermonuclear plasma with various impurities and increased erosion rate of reactor materials. One of the factors increasing the probability of a unipolar arc occurrence is a change in the surface morphology of tungsten diverters. Under the influence of helium ions flow, filamentous nanostructures called fuzz are formed on the tungsten surface [1,2]. To study an unipolar arc, it is necessary to measure its operation time.

The experimental technique consisted of measuring the arc operation time at direct current. In total, 6 different current values were used from the threshold current value 0.17 A to 0.7 A. Special attention is paid to the rapid destruction of the fuzz layer. The arc was ignited using a trigger electrode, and after 20 to 50 discharges, the trigger electrode was moved to another location. Approximately 600 arcs were measured for each current value. All experiments were carried out in a vacuum chamber at a pressure no higher than 10^{-8} torr. The trigger electrode and anode were made of tungsten. The arc power source was a 450 μF capacitor charged to 200 V. The current values were recorded using a 0.33 Ω shunt connected to an oscilloscope. Figure 1 shows examples of arc current waveforms.

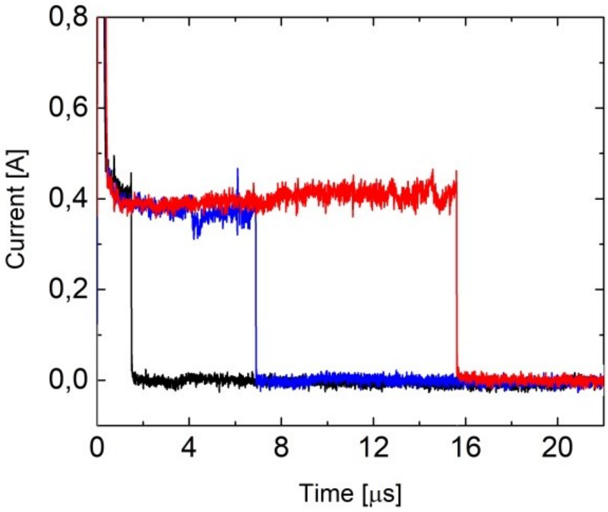

Fig.1. Example of waveforms of the arc current.

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G1-O-008602

INVESTIGATION OF THE PROCESSES OF STABLE BURNING OF THE ARC AND ITS EXTINCTION AT THRESHOLD CURRENTS

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The processes of combustion and extinction of a vacuum arc discharge were studied at an extremely low current level. In this case, a high-voltage cable generator of rectangular pulses with a duration of up to 1.3 μs was used as a current source. The cathode was remelted in vacuum forming a drop-shaped edge. The experimental setup is presented in Fig 1.

Under these conditions, when the discharge is interrupted, the initial high-voltage voltage (up to 30 kV) is instantly established in the interelectrode gap.

During the measurements, the discharge current, the discharge glow, and the floating potential of the plasma were recorded. Features of spontaneous extinction of the arc current were revealed. The response of the plasma glow and the floating potential of the plasma to the process of interruption and resumption of the arc discharge was also obtained.

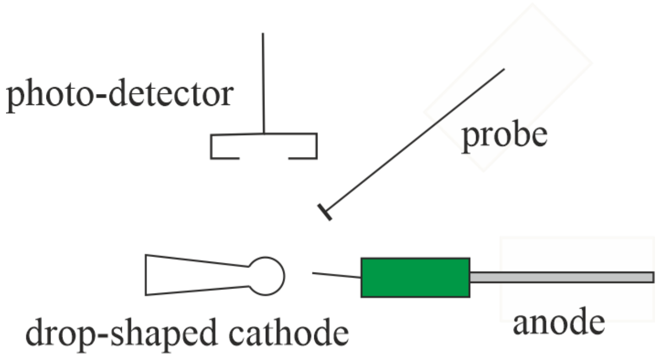

Fig.1. The experimental setup.

DYNAMICS OF THE WIRE DISCHARGE ANODE PLASMA IN AN ELECTRON SOURCE BASED ON ION-ELECTRON EMISSION

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In electron sources with plasma emitters, which include sources based on ion-electron emission [1], the parameters and dynamics of the emission plasma affect the formation of ion-electron optics, discharge current switching, emission of charged particles into the accelerating gap and, as a consequence, to the generation of an electron beam [2]. That is why studies is being carried out to measure the parameters of the emission plasma and determine their dependence on the conditions for generating the discharge and electron beam.

Previously, it was shown that the transition from a direct current mode of wire discharge generation to a repetitively pulsed one with a frequency of tens of kilohertz leads to an increase in the coefficient of electron beam extraction from vacuum to the atmosphere [3]. In this work, the dynamics of the anode plasma in the repetitively pulsed generation mode was studied by measuring the distribution of the electron beam current density in the atmosphere. Since the generation of an electron beam in electron sources based on ion-electron emission largely depends on the parameters of the anode plasma and its distribution, then by recording the dynamics of the electron beam using a sectioned collector (Fig. 1), one can estimate the development of the anode plasma in the space of the plasma emitter.

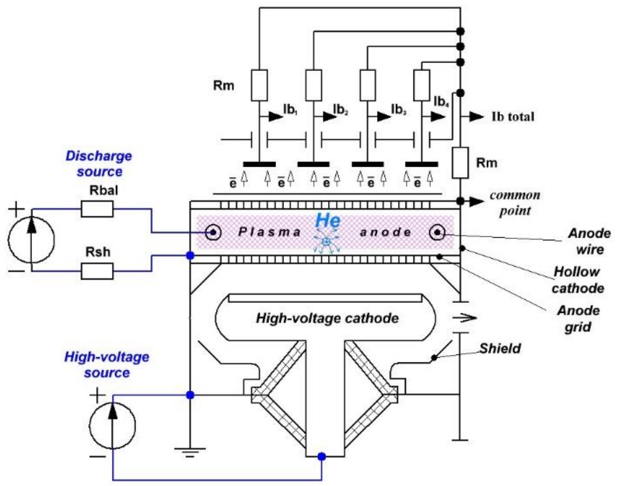

Fig.1. Schematic diagram of an electron source with a sectioned collector.

The applied mode of repetitively pulsed anode plasma generation made it possible to generate an electron beam 650×450 mm in size with an inhomogeneity of ± 15 %, which is important for equipment of this class.

The work was carried out within the framework of the Russian Science Foundation project No. 20-79-10015-P.

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STUDY OF BARRIER PULSE-PERIODIC ATMOSPHERIC PRESSURE GAS DISCHARGE AT HIGH PULSE REPETITION FREQUENCIES*

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Homogeneous (diffuse) glow discharges occurring at atmospheric working gas pressure are attractive sources of nonequilibrium nonstationary plasma with a wide range of applications. Currently, electrophysical devices for generating high-voltage pulses with nanosecond and subnanosecond fronts allow to ignite the gas discharge at high pressures and provide volumetric character of current flow in the time range, less than the time of spark processes development. Appearance of commutation semiconductor and gas-discharge devices of nano- and subnanosecond range functioning at high pulse repetition frequencies gave an opportunity to investigate original properties of atmospheric pressure discharge at pulse repetition frequencies of tens to hundreds kHz. This is interesting from the point of view of introduction of significant pulse and medium pumping powers into the working media.

The aim of this work was to study the conditions of volumetric current flow in atmospheric pressure gases using the physical and technical capabilities of switching devices - eptrons for generating high-voltage (up to ~ 40 kV) short (~ 10-30 ns) pulses with nanosecond fronts and capable of functioning at high pulse repetition frequencies (up to $f \approx 100$ kHz).

The studies were carried out in a cell designed to implement and study a simple high-voltage gas discharge between flat electrodes: a titanium anode and a dielectric cathode with a diameter of 19 mm (cathode–anode distance 7 mm) in the mode of a train of pulses with a train frequency of 10 Hz with a filling frequency of regular pulses f = 5–100 kHz and voltage amplitude U = 2–35 kV with adjustable pulse front duration τ = 1.5–10 ns in helium at atmospheric pressure. A feature of the cathode was that it consisted of a set of Al_2O_3 plates with a thickness of ~0.6 mm, which made it possible to change the cathode thickness h in the range h = 2–7 mm.

Dependences of current amplitude on voltage amplitude I(U) at different pulse repetition frequencies f= 25, 50 and 100 kHz with cathode thickness h = 7 and 2 mm were studied. At U > 10 kV in the cuvette a spatially homogeneous - diffuse discharge occurs and up to $U \approx 30$ kV a volumetric current flow was observed. The combination of results demonstrated that I(U) do not depend on pulse repetition frequency; in the cuvette with thinner cathode, other things being equal, ~3 times higher currents are achievable, but with decrease of operation limiting frequencies (the discharge moves faster from volumetric to filament stage); reduction of the excitation pulse front duration τ does not affect the value of achievable current, but allows increasing the limit operating voltage with preservation of the volumetric character of current flow, while decreasing the pulse repetition frequency does not change the picture. Experiments have shown that the time delay of the maximum current from the beginning of voltage at different voltage front durations at different frequencies decreases with increasing U and for smaller τ more rapid development of the discharge and larger achievable voltages are characteristic. The results of the experiments demonstrated that decreasing the pulse repetition frequency is accompanied by improving the stability of the discharge. Numerical simulation of gas discharge ignition in helium at p_{He} = 1 atm was performed within the framework of the hydrodynamic approach in a two-dimensional setting with cylindrical symmetry

* The work was supported in part by the RSF Grants No. 19-19-00069

NUMERICAL STUDY OF THE DYNAMICS OF A MICROWAVE DISCHARGE IN THE ANTINODE OF A STANDING ELECTROMAGNETIC WAVE IN INERT GASES

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Studies of electrodeless microwave discharges in atomic and molecular gases [1, 2] are very relevant for many applications. Experimental studies have shown that microwave discharges in free space can be realized in two main forms: diffuse and filamentous forms [3, 4]. A wide variety of physical processes occurring in a microwave discharge and their high rates make experimental diagnostics of the plasma parameters of such discharges extremely difficult. It is possible to obtain only integral or estimated values of the main characteristics and mainly by indirect measurements and estimates [2]. In this regard, the progress of experimental research and practical applications stimulates the construction of self-consistent physical and mathematical models of microwave discharges and numerical calculations to study the plasma dynamics depending on the pressure and type of gas, the magnitude and time of the input power, etc. In the present work, on the basis of the self-consistent model of a microwave discharge that we formulated earlier [5], numerical calculations were carried out to study the dynamics of the stretching of a single microwave discharge and its transition from a diffuse form to a filamentous one, depending on external parameters.

The paper presents the results of numerical calculations on plasma dynamics in a microwave discharge in argon and helium under the experimental conditions from [1].

The model was based on the balance equations for charged and excited particles, the balance equations for the energy of electrons and the heavy plasma component, and the system of Maxwell equations for describing the microwave electromagnetic field [3]. To describe the discharge in helium, we used a set of plasma chemical reactions taken from [3]. Two excited atomic and one excited molecular states of helium were taken into account, as well as two kinds of ions. To describe the microwave discharge in argon a set of reactions from [4] was considered. The rates of inelastic processes with the participation of electrons were determined using the Maxwellian EDF and the EDF obtained in the framework of the local Boltzmann kinetic equation.

As a result, the dynamics of the breakdown of the microwave discharge and its elongation along the oscillating electric field is presented. A transition from a diffuse to a contracted (filamentous) form of a microwave discharge in argon is demonstrated. In helium, a diffuse discharge was observed in the considered time range (up to 20 μs). Quantitative agreement was shown in electron density with experimental data in hellium [3].

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DYNAMICS AND KINETICS OF RUNAWAY ELECTRONS IN DENSE GASES IN A STRONGLY NONUNIFORM ELECTRIC FIELD*

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Runaway electrons (RAEs) are traditionally understood as free electrons in a gas or plasma that lose less energy in collisions with particles of the medium than they gain under the action of an applied electric field and, as a result, are continuously accelerated [1–3].

In the present work, we analyze the features of electron runaway in an electric field that is inhomogeneous due to the use of a conical cathode (see, for example, experiments [4,5]). The field decreases with distance from the cone apex according to the power law $E \sim r^{\gamma-1}$, where the exponent γ lies in the range $0 < \gamma < 1$ (its value depends on the opening angle of the cone). Two different runaway criteria were compared (the results of calculations are shown in Figure 1). The first, traditional criterion assumes the continuous acceleration of an electron throughout the entire interelectrode gap. The second criterion assumes that a fast electron reaches the anode without requiring its continuous acceleration, i.e. its deceleration is permissible in some regions of the gas gap. Based on the results of our analysis, the range of admissible values of the exponent γ is divided into two parts, $0 < \gamma < 0.5$ and $0.5 < \gamma < 1$, corresponding to the cases of weakly and strongly inhomogeneous field distributions. For a weakly inhomogeneous field (conical cathodes with opening angles exceeding the threshold of 98.6 degrees), the dynamics and kinetics of electrons are generally similar to the case of a uniform field ($\gamma = 0$), and the use of different runaway criteria does not lead to differences in the threshold values of the voltage applied across the gap. The effects that led to the need to refine the runaway criterion (deceleration of free electrons at the periphery) arise under conditions of a strongly inhomogeneous field (conical cathodes with subthreshold opening angles). Here there are significant differences (up to 2.4 times) in the threshold voltage values for different runaway criteria (see Figure 1).

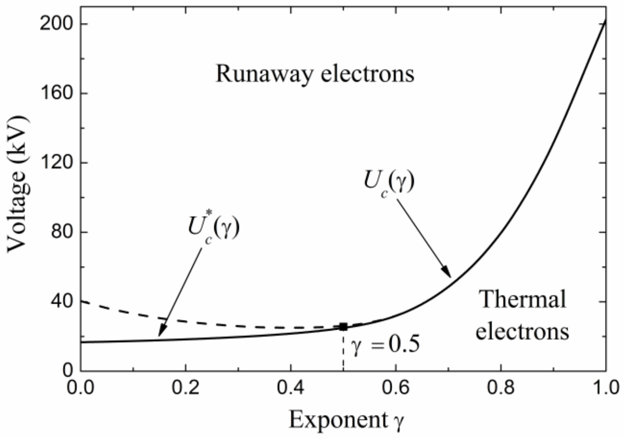

Fig. 1. Dependences of the threshold voltage for electron runaway on the field inhomogeneity parameter γ for two different runaway criteria. The dashed line (U_c) corresponds to the continuous acceleration of an electron in the gas gap. The solid line (U_c^*) corresponds to a fast electron reaching the anode with an energy exceeding 100 eV. Interelectrode distance is 7.5 mm; gas is nitrogen at atmospheric pressure.

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INFLUENCE OF THE DOWNSTREAM REGION TO THE INTERRUPTION ABILITY OF THE HV GAS-BLAST INTERRUPTERS

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One of the main directions of the HV gas-blast interrupters (GBI) modernization is to increase the rated voltage and rated current per one break. The SF6 is widely used in the modern GBI for 50-63 kA, 330-500 kV and higher with additional shunt capacitance for today, that's why the research of the SF6 effective use is very important.

It is known the downstream area has a significant effect on the auto-puffer with (or without) heating volume GBI interruption ability with an increase of the rated voltage [1, 2]. The pressure ration in such type of GBI is not much more than the critical pressure ratio. With an increase the rated voltage and interruption current the length between contacts increases. The insulation nozzle diameter increases too due to the intense nozzle wall ablation [1, 3]. These factors lead to the mass flow rate fall dawn, that is affected on the GBI interruption ability.

An additional mass flow rate from the wall at the nozzle throat is one of the possible ways to solve the problem [4]. This additional flow is directed into the downstream area. It is known that the temperature along the arc axis decreases non-uniformly, and its lowest value corresponds to the region of the nozzle throat and the adjacent diffuser region [2, 3]. If the length between contact increases, the GBI interruption ability decreases due to the pressure gradient reduction, attenuation turbulence effect, shock wave near the nozzle outlet and other effects in the downstream area. Mass flow rate of SF6 through the additional channel between the nozzle throat and compression volume can lead to a change of the flow distribution in the diffuser and some increase in the area with the non-conductive gas, which is necessary for success arc decay. By changing the angle of attack of the flow from the channel inlet, the flow parameters are selected to achieve the best results.

Numerical simulation is used to estimate the influence of the attack angle on the GBI interruption ability. Some calculation results are presented.

In the paper the effect of the additional SF6 mass flow rate to the downstream area of the insulation nozzle and its influence on the GBI interruption ability are discussed.

The research was carried out within the state assignment of Ministry of Science and Higher Education of the Russian Federation (theme No. FSEG-2023-0012). The results of the work were obtained using computational resources of the supercomputer center in Peter the Great Saint-Petersburg Polytechnic University Supercomputing Center (www.spbstu.ru).

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ANALYSIS OF THE TURBELENCE INFLUENCE IN THE ELECTRIC ARC PLASMA FLOW BY THE LABORATORY STUDY METHOD

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In the course of the work, experimental studies of the motion and heating of a fine powder particle in a plasma flow were carried out [1]. A cross-analysis of the effect of plasma flow turbulence on the movement and heating of a fine powder particle was carried out, and the results of experiments demonstrating the positive effect of the degree of plasma flow turbulence [2] on the heat exchange processes between plasma and fine powder - the technological efficiency of the installation (Figure 1) are indicated. In each study, the desired values were determined by varying the parameters of the deposition process – the speed of material feed (experiences 2-4) and the speed of plasma gas flow (experience 1), which directly affect the degree of flow turbulence [3]. As a result, the following are optimal for the process: the ratio of the supply intensity of the plasma-forming gas and the sprayed material is equal to 1:1.5; modes of operation in the transitional nature of the movement of the gaseous medium [4].

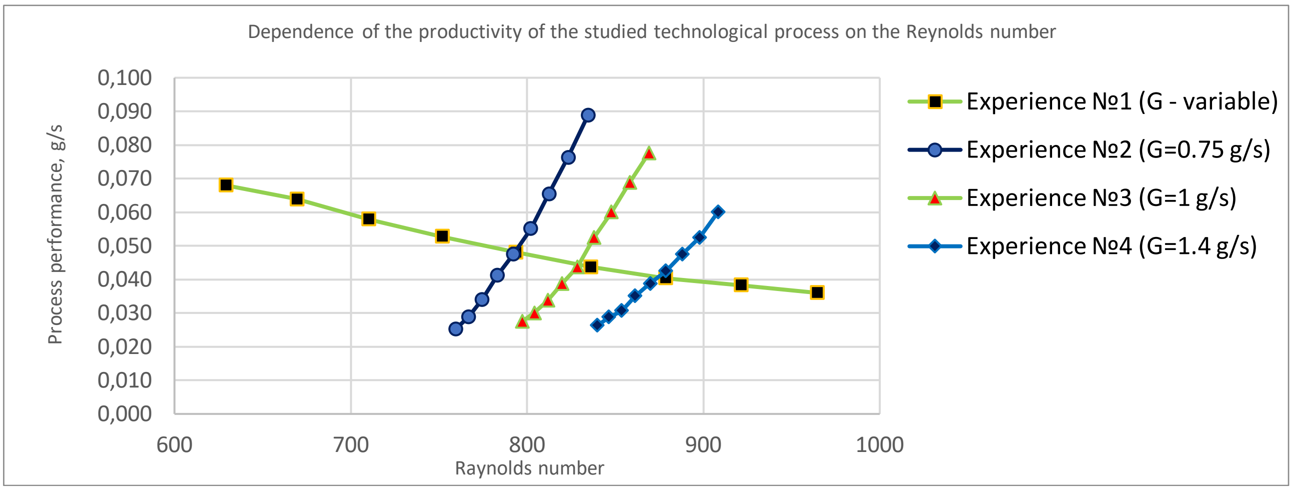

Fig.1. Comparative laboratory results

The decrease in the productivity of the process in the first experience is due to the fact that the generalized effect of reducing the trajectory of the particles and increasing the speed of their movement leads to the fact that the time spent by the particles in the flow becomes insufficient to melt the particles of a large fraction, which entails a decrease in the mass gain with an increase in the flow rate of plasma gas (longitudinal component). It should be noted that in the region of transition of the nature of the flow motion changed to the turbulent regime, there is a slight decrease in the steepness of the drop of the studied characteristic. With a grow up of the flow intensity characteristic in the powder material moving process (transverse component), the trajectory of the particles increases, which increases the time spent by the particles in the plasma flow, which, in common with a positive effect on the transition of the nature of the flow to turbulent, leads to an increase in productivity, and hence - efficiency.

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TIME-OF-FLIGHT ANALYZER OF THE PLASMA MASS-TO-CHARGE COMPOSITION WITH A SECONDARY ELECTRONIC MULTIPLIER

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One of the widely used tools for studying the plasma of discharges of various types is the time-of-flight analyzer of the plasma mass-charge composition. The feature of its application is the determination of the plasma parameters based on the analysis of the parameters of the ion beam extracted from it. The measurement technique is based on the deviation of a short time sample of the ion beam from the initial direction to the place where the ion current is measured and the separation of groups of ions with different charge-to-mass ratios during the flight of a drift gap of a fixed length [1]. The time-of-flight spectrometer has a sufficiently high resolution, relatively high sensitivity, and a wide range of ion mass measurements, from hydrogen to uranium [2]. Its essential advantage is the possibility of measuring all beam components simultaneously at any moment of discharge burning.

Time-of-flight analyzers of the mass-charge composition are actively used to study the ion beam in vacuum-arc ion sources with different parameters [3, 4], sources generating mixed beams of gas and metal ions [5], as well as to study gas discharge plasma in crossed electric and magnetic fields, for example, a magnetron discharge [6]. Typically, the analyzer uses a magnetically insulated Faraday cup to measure the ion current. However, in some cases, especially when studying low-current gas discharges, the sensitivity of the analyzer is not enough to accurately record all mass-charge groups of ions in an ion beam. This problem can be solved in various ways, such as by amplifying the output signal taken from the Faraday cup, or by using more sensitive ion current detectors, such as a secondary electron multiplier (SEM).

In this paper, we compare the measurements of the mass-charge composition of the vacuum arc discharge plasma using a time-of-flight analyzer using a Faraday cup or SEM as a sensor. The vacuum-arc discharge was chosen because, with typical operating parameters of such a discharge (an arc current pulse amplitude of hundreds of amperes; a pulse duration of hundreds of microseconds), its plasma, depending on the cathode material, has a wide range of charge states, from 1+ to 5+ [2]. Al, Cu, Ti, Mo, Ta, and Bi cathodes were used for the experiments. It has been shown that the difference between Faraday cup and SEM measurements is a few percent, which is an acceptable measurement error for most applications. It is shown that SEM in all cases gives a lower percentage of ions of high charge states in the plasma than the Faraday cup. An explanation for these differences is given.

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ANALYSIS OF ION FLUX AND OPTICAL EMISSION FROM AN IMPULSE NON-SPUTTERING MAGNETRON DISCHARGE*

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Highly ionized gas discharge plasmas where the damage of cathode or anode due to sputtering or evaporation is low, attract significant attention because of their potential applications in a wide scope of research- and technology-oriented processes, such as electric propulsion (development of plasma thrusters), material testing under high thermal and plasma loads, material etching, and high-power switching [1–4].

In this study, impulse non-sputtering discharge in hydrogen and helium has been examined. The pulse duration was around 1 ms, and the maximum pulse power was around 80 kW. The plasma parameters were monitored with an electric probe. Optical emission spectra from plasma were recorded synchronously with each pulse by AvaSpec ULS2048 three-channel spectrometer. Along with registering optical emission, a dedicated mass-analyzer with Wien ($E\times B$) filter was used to measure the mass-resolved flux of ions escaping the magnetic trap. Experimental setup scheme is shown in Fig. 1.

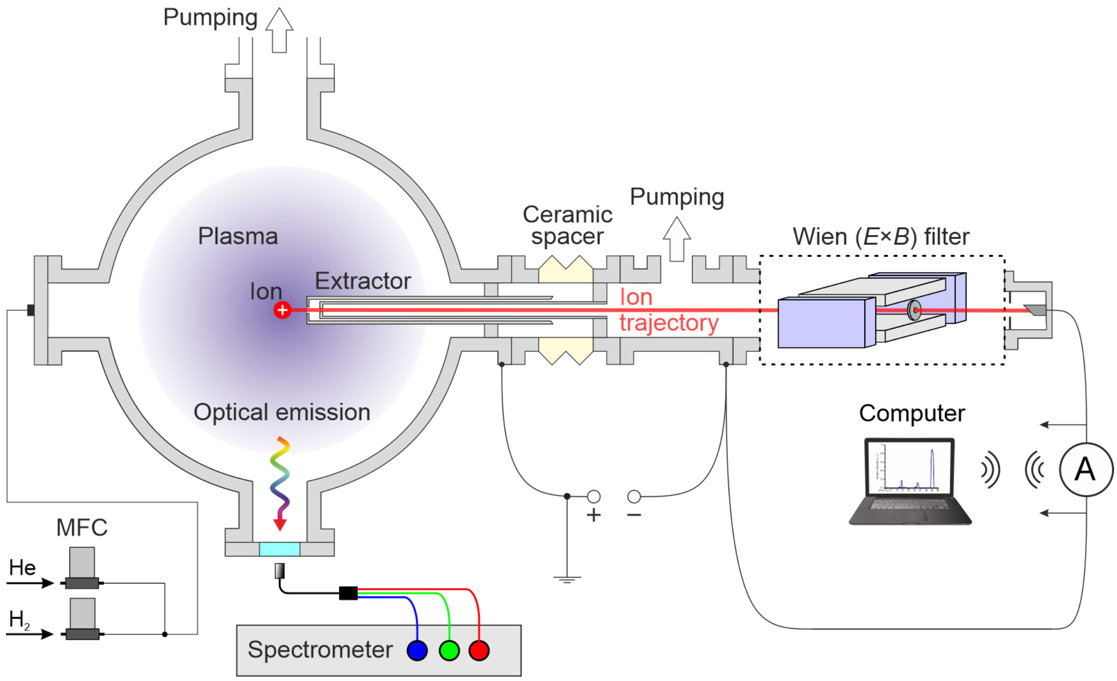

Fig.1. Experimental setup scheme.

The use of the pulsed non-sputtering modes in hydrogen and helium enables achieving non-constricted plasmas with high density and no evidence of optical emission lines corresponding to the species of cathode or anode materials. Ion mass spectrometry reveals intense production of metal ions once the discharge becomes constricted and an arc is formed.

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MONTE CARLO SIMULATION FOR ELECTRON AVALANCHES AT HIGH REDUCED ELECTRIC FIELD AS APPLIED TO TOWNSEND DISCHARGE CURRENT IN NITROGEN

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This work addresses the Monte Carlo simulation of the steady-state prebreakdown current with ionization multiplication at a low nitrogen pressure. The conditions of modeling correspond to the product of gas pressure by the gap distance in a vicinity of minimum of the Paschen's curve when the high reduced electric fields, E/p = (200–660) V/(cm·Torr), are achievable in the nonself-sustained discharge. The main idea in description of the steady-state mode is that the current in external electric circuit is provided by a great number of electron avalanches simultaneously generated in the gap.

The results of modeling are compared with the experiments [1–5] in which the impact ionization coefficient α (the first Townsend coefficient) is obtained based on measuring the prebreakdown current. It turned out that the calculated coefficient α is in a good agreement with the experiment. However, the interpretation of the process of electron multiplications needs in corrections.

The classical impact ionization coefficient is conventionally introduced with invoking the notion of the electron drift velocity. Besides, it is implied that the size of electron cloud is determined by the process of radial diffusion of electrons. In the case under consideration, the runaway electrons, which move in the regime of continuous acceleration, mainly contribute both in the expansion of the electron cloud in longitudinal and transverse directions and in the ionization multiplication of the initial emission current.

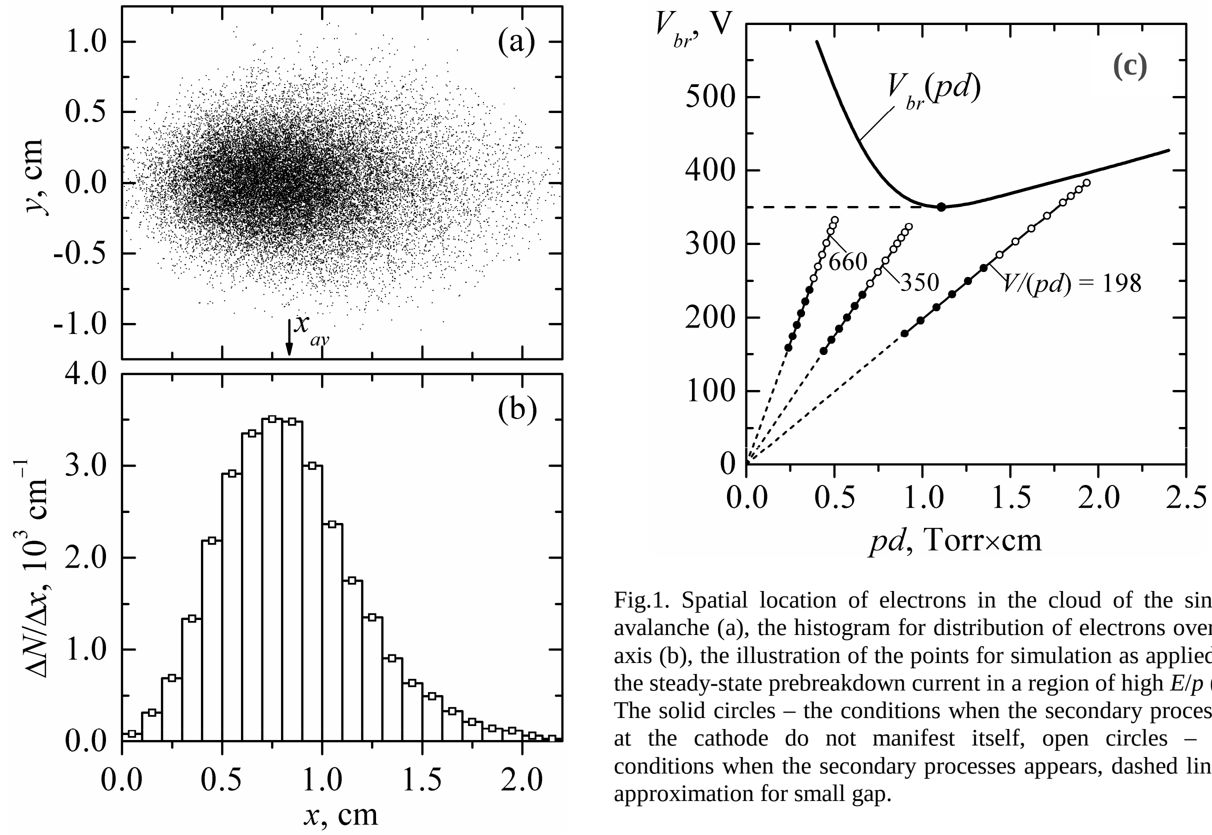

Fig.1. Spatial location of electrons in the cloud of the single avalanche (a), the histogram for distribution of electrons over x-axis (b), the illustration of the points for simulation as applied to the steady-state prebreakdown current in a region of high E/p (c). The solid circles – the conditions when the secondary processes at the cathode do not manifest itself, open circles – the conditions when the secondary processes appears, dashed line – approximation for small gap.

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SIMULATION OF AUXILIARY GLOW WIRE DISCHARGE WITH A HOLLOW CATHODE IN THE ELECTRON ACCLELERATOR

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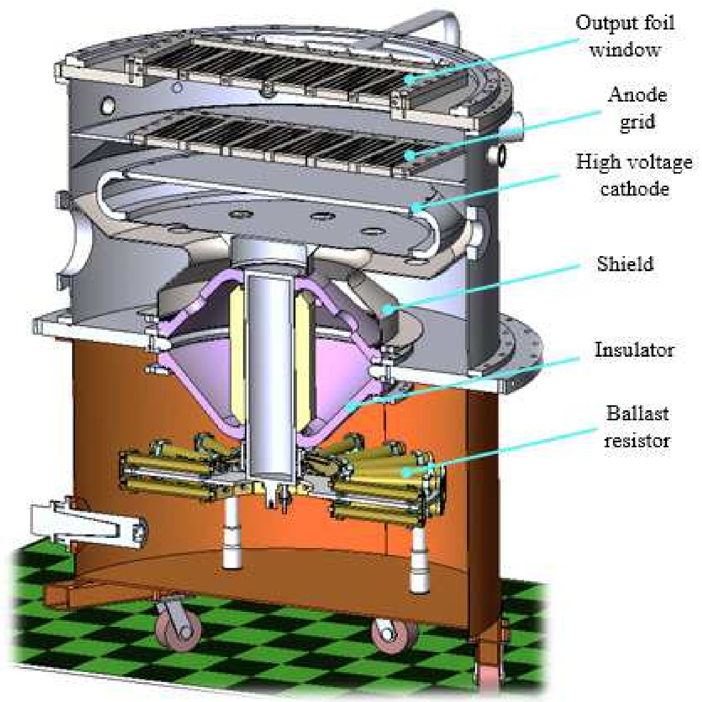
The region of the auxiliary discharge of an electron accelerator based on a non-self-sustaining high-voltage glow discharge is studied [1–3]. An orbitron discharge with a hollow cathode is used as a source of emission plasma in which the anode is two thin tungsten wires and the cathode is the walls of the chamber. Numerical simulation using OOPIC Pro (xoopic) [4] and KOBR3-INP [5] codes is used to study the dynamics of discharge and the coefficient of electron beam extraction into the atmosphere. Several fundamentally different configurations of the extraction grid were simulated. Thick massive grid for which the electric field from the main gap does not effected to the auxiliary discharge; thin grid when the electric field partially affects the area of the auxiliary discharge and a thin fine-grained grid with a low transparency coefficient. The conditions for the continuous generation mode and for the repetitively pulsed mode with the addition of a control circuit for the potential of the extracting grid in the pause between the generation pulses were simulate. We aimed to form a clear and understandable model of the behavior of the auxiliary discharge plasma depending on external conditions, which would allow us to predict data on the configuration of the ion-electron optical system.



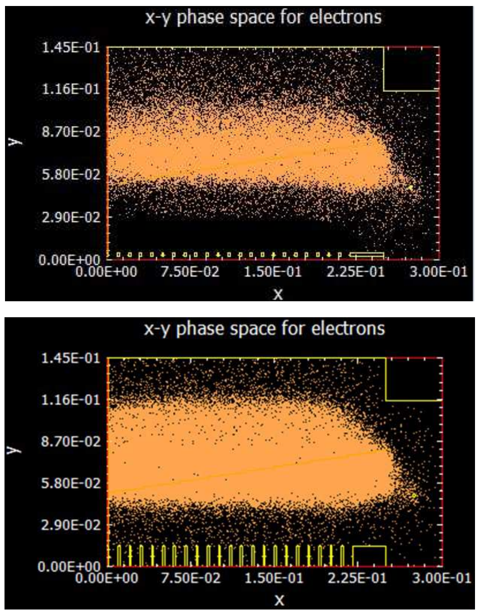


Fig.1. Design of a simulated wide-aperture electron accelerator and the part of an auxiliary discharge region with plasma distribution for two different anode grids.

As a result, various regimes of electron beam generation were obtained, both efficient, with a high coefficient of electron beam extraction into the atmosphere, and regimes in which the influence of various destabilizing factors leads to low accelerator efficiency. The results obtained for the generation regimes were compared with the experimental results. The simulation showed good agreement with the experiments and made it possible to determine the optimal conditions for the maximum coefficient of electron beam extraction into the atmosphere.

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DIFFUSE PLASMA JETS SIMULATING COLUMNAR SPRITES AND THEIR PARAMETERS

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In view of the significant progress in technology, over the past three decades, scientists have been actively studying electric discharge phenomena occurring in the upper atmosphere of the Earth [1]. Among the whole variety of Transient Luminous Events (TLEs), considerable attention is paid to the study of red sprites, in particular column-like (columnar,) that occur at altitudes above 50 km [2, 3]. The study of these phenomena is usually carried out in natural conditions with the help of ground-based laboratories, as well as aircraft, satellites, and the International Space Station. Since such studies are quite expensive, researchers are making attempts to create laboratory setups that make it possible to model and characterize high-altitude atmospheric phenomena.

In one of the recent papers, a setup (Fig.1) was proposed that allows the formation of diffuse plasma jets in low-pressure air, which the authors associate with miniature models of red columnar sprites [4]. The similarity of diffuse plasma jets to red sprites is justified by the results of spectral measurements, as well as by measuring the velocities of the ionization waves (streamers) responsible for their formation, which turned out to be similar to those observed under similar conditions in red sprites.

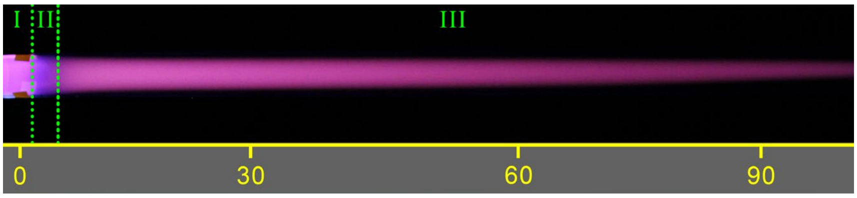

Fig.1. Setup (quartz tube with external electrodes) for the formation of a streamer discharge in low-pressure air. I – main (interelectrode) discharge zone; II – near-electrode zone; III – diffuse plasma jet zone. Air, 0.2 Torr, U_0 = -7 kV.

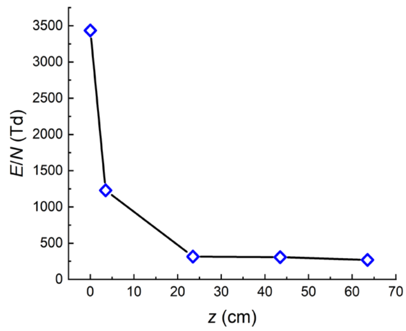

Fig.2. Reduced electric field strength E/N versus distance from z = 0 to 63.5 cm. Air; p = 0.2 Torr, U_0 = -7 kV.

No less interesting is the comparison of laboratory and natural phenomena in terms of plasma parameters. Using the methods of the optical emission spectroscopy (OES) the main plasma parameters in a plasma diffuse jet and a main discharge providing the formation of the jet were measured. There are data on the distribution of the reduced electric field strength E/N (Fig.2), as well as the electron T_e, vibrational T_{vib}, rotational T_{rot} and translational T_{tr} temperatures along the longitudinal axis of the tube, where diffuse plasma jets are formed. These results confirm the results of studies of natural sprites, as well as the streamer mechanism for the formation of the jets (sprites). The correctness of the measurement of plasma parameters is confirmed by the results of modeling the emission spectra of plasma using the SPECAIR code – the plasma parameters measured in the experiment make it possible to obtain in the simulation spectra identical to those recorded experimentally.

The study is funded by the Ministry of Science and Higher Education of the Russian Federation within Agreement No. 075-15-2021-1026 of November 15, 2021.

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VOLUME DISCHARGES AT SUPERATMOSPHERIC PRESSURE IN CO_2–LASER MIXTURES WITH HIGH PUMPING ENERGY DENSITY

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The transition from atmospheric pressure to superatmospheric in TE–CO_2 lasers ensures the achievement of higher values of radiation energy per pulse at a shorter duration.

Successful implementation of spatially homogeneous volumetric pumping discharges at superatmospheric pressures is possible if a sufficiently high level of initial ionization of the working gases in the interelectrode gap is ensured. Efficient absorption of ionizing VUV radiation by carbon dioxide molecules requires a maximum reduction in the distance between the source of initial ionization and the gap for ignition of a volume discharge.

The problem of increasing the intensity of the source of ionizing VUV radiation and its location very close to the main gap was solved by using a three-electrode structure with successive ignition of an auxiliary preionization corona discharge and a volume discharge. The main discharge gap was formed by a monolithic profiled graphite electrode and a flat grid electrode. The volume of the excited plasma in this gap was V = 7.5x0.8x0.8 cm = 4.8 cm^3. The auxiliary electrode in the form of two strips of molybdenum was located above the grid electrode. The value of this gap was 0.4 cm. A high-voltage pulse was applied to the contacts of the auxiliary electrode and cathode of the main gap. At the initial moment, an auxiliary high-current corona discharge is ignited and illuminates the main gap through the grid anode. This process continues during the charging time of the "anode-cathode" constructive capacitance. After that, a breakdown of the main gap occurs with the current flowing through both gaps connected in series.

During the research typical gas mixtures CO_2:N_2:He were used in the ratios 1:1:2 (1), 1:1:3 (2), and 1:1:6 (3).

As a result of this work, the following new data were obtained:

1. The pumping energy increases linearly with pressure within 1–5 atmosphere and at pressures of 5 and 6 atmosphere for a mixture CO_2:N_2:He = 1:1:2 is 4.5 J.

2. The maximum values of the pumping energy density are typical for a pressure of one atmosphere and are, respectively, for mixtures 1:1:2 – 400, 1:1:3 – 320 and 1:1:6 – 200 $mJ\cdot cm^{-3}\cdot Atm^{-1}$. As the pressure increases to 6 atmospheres, the pumping energy density decreases to 150, 140, and 100 $mJ\cdot cm^{-3}\cdot Atm^{-1}$, respectively.

CHARACTERISTIC OF PLASMA JETS FORMED BY GLOW DISCHARGE IN "GLIDING ARC" ELECTRODE SYSTEM *

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Currently, plasma jets formed at the basis of the atmospheric-pressure discharges are attracting increasable attention [1-7]. Typical examples of gas discharge systems used for obtaining discharge in a gas flow and plasma jet are so-called plasmatron and "gliding arc" [1–4]. The electrodes of these systems are configured to allowing the carrier gas to flow through the discharge region. Thus, the flow of heated and weakly ionized gas, so-called "plasma jet", forms [1, 6, 7].

The present work deals with the investigation of atmospheric-pressure gliding glow discharges in the electrode system of "gliding arc" and characterizing the properties of "plasma jets". Schematic of the electrode design and electric circuit for discharge powering are shown in fig. 1.

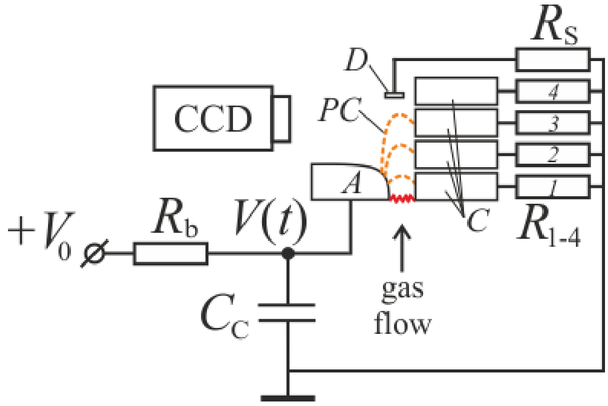

Fig.1. Schematic of the electrode design and electric circuit for discharge powering. *A* – anode, *C* – sectioned cathode, *D* – diagnostics electrode, *PC* – position of the discharge column at a later temporal stage of discharge development. V_0 = 3 kV, R_b = 20 kΩ. C = 300 pF, $R_{1\text{-}4}$ = 1 Ω.

The discharges in airflow and in argon flow gliding arc-type electrodes have been investigated using oscillography methods and CCD camera photography. Waveforms of discharge current and current through the plasma jet using the system of diagnostic electrode are obtained. The feature of the electrode design is that the cathode is sectioned, and current to each section is measured separately by shunts $R_{1\text{-}4}$. Thus we have the ability to investigate the features of negative glow displacement during the discharge gliding. The gas temperature in the plasma jet is measured using thermocouple. Comparison of the features of discharge behavior and jet parameters in argon and in the airflow is carried out.

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G1-P-004602

MECHANISM OF TRIGGERING FOR THE PSEUDOSPARK SWITCH WITH A TRIGGER UNIT BASED ON STEADY-STATE AUXILIARY GLOW DISCHARGE*

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The pseudospark switch is the high current switching device that depends on a pulsed low-pressure gas discharge with hollow cathode [1–4]. In this device, a great variety of the methods for triggering can be realized [2]. One of the methods that allows the nanosecond stability of the switch triggering is based on a usage of the trigger unit with auxiliary glow discharge [2–4]. In this report, we present the new data on operation of the trigger unit with hollow cathode and hollow anode. The main data of the report are associated with elucidation of the mechanism of the switch triggering when the trigger pulse is applied to the trigger electrode system.

Schematic of the demountable pseudospark switch jointly with the electric circuit is shown in Fig. 1. The working gas in the switch is hydrogen. Trigger unit electrodes are symmetrical and each electrode has the inner diameter of 36 mm with the depth of the cavity of 45 mm. Auxiliary discharge current was at a level of 20 mA.

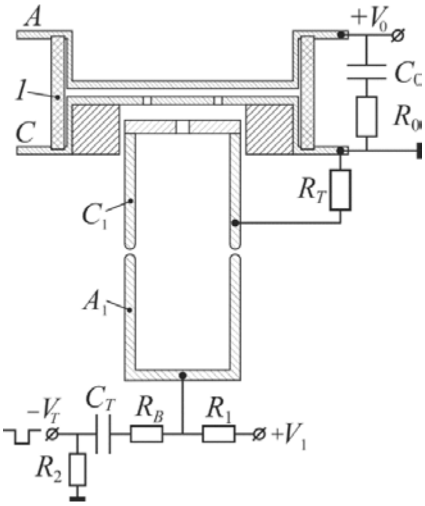

Fig.1. Schematic of the switch and the electric circuit illustrating the method for triggering.
1 - ceramic casing for the main high-voltage electrodes, *A* – main anode, *C* – grounded main cathode, A_1 and C_1 – hollow electrodes of the trigger unit with the auxiliary glow discharge.
V_0 = 5–20 kV, C_0 = 4 nF, R_0 = 18 Ω, V_1 = 0.4–3 kV, R_1 = 55 kΩ, V_T = 2–3.5 kV, R_2 = 100 Ω, C_T = 230 nF, R_B = 50 Ω, R_T = 5–50 kΩ.

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It is shown that when the electrode C_1 plays of role of the hollow cathode in the auxiliary discharge, the parasitic current via the aperture is provided by the ion flow. Then this current does not influence on the static breakdown voltage of the main gap. Applying the trigger pulse leads to the situation when the discharge between the trigger electrodes is intensified and the electrode with aperture turns out into the hollow anode. In these conditions, the current of the pulsed trigger discharge is intercepted through the aperture to the main electrode system and the switch is triggered. Optimization of the electrode geometry in the trigger system with the aim to decrease the delay time to triggering the switch was carried out. Minimum delay time 70 ns is achieved.

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DEVELOPMENT OF A TECHNIQUE FOR CORRECTING IMAGES OF ELECTRODE SPOTS OBTAINED WITH A NEWVIEW 5010 SURFACE STRUCTURE ANALYZER

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The spark discharge method is one of the most promising ways for the nanopowder synthesis. This is the gas-phase method for the obtaining of nanoparticles, based on the evaporation of metal electrodes under the action of a spark discharge current. The method already finds a number of applications in various technological areas, such as microelectronics [1], medicine [2], catalysis [3], etc. The main advantage of the method compared to others is the high purity and low average diameter of the obtained nanopowders. The particle size obtained by this method can reach several nanometers [4, 5]. However, the method has a some specials, this is low productivity of nanopowders [6], which limits the scope as a method for obtaining structural nanomaterials.

One of the approaches to a possible solution to this problem can be the study of the nature of the erosion of the electrode material as a result of a spark discharge. Taking into account that the height difference on the surface of a spot from a spark discharge can reach up to one hundred micrometers, one of the most acceptable approaches for research purposes is interference microscopy.

In the current report, we have studied spots of single discharges of various energies (from 5 to 19 J) deposited on a flat polished surface of an electrode made of iron. The surface structure analyzer NewView 5010 from Zygo (USA) was used as measuring equipment.

However, a number of difficulties arose during the microscopy. Images taken with a microscope have non-physical features, such as data missing data points, spikes, and surface noise. The reasons for their occurrence are the steep slopes of the surface of the discharge spots, as well as, apparently, the low reflectivity of individual areas. Since a completely filled data array is more desired to analyze the physical parameters of the discharge spots, a technique for restoring images by weighted average interpolation followed by smoothing the results was developed.

In addition, based on the constructed interpolation algorithms, a window application for the Windows operating system was developed that is capable of expressly interpolating the initial microscope data, creating a visual height map and saving the restored data array as a text file.

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SIMULATION OF HIGH CURRENT VACUUM ARC WITH HYBRID CATHODE ATTACHMENT

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This paper is devoted to modeling of high current vacuum arc (HCVA) with so called hybrid cathode attachment (HCA). The HCA is cathode attachment which combines separate cathode spots and continues thermionic erosion attachment. This attachment can appear when average near-cathode plasma density produced by the cathode spots is in the order of 10^{18} cm^{-3} (Fig. 1.), and cathode surface temperature between the cathode spots is about of 3.5 kK. According to preliminary calculation the HCA can exist in HCVA with an average cathode current density of more than 10^5 A/cm^2. The appearance of such kind of attachment can explain a strong increase in specific cathode erosion, which was measured in experiments where vacuum arc plasma gun was used for pumping a plasma liner for plasma puff z-pinches ([1] for example).

In order to have possibility to model HCVA with HCA a special numerical model was developed. This model, among other things, self-consistently calculates heat fluxes to the cathode, cathode heating with subsequent evaporation and plasma formation in parallel with the plasma inflow from cathode spots. For plasma dynamic calculations a hybrid model previously developed in [2] is used. This hybrid model treats the ion subsystem with a particulate approach but treats the electron subsystem with a magnetohydrodynamic approach. The development of the HCVA is calculated for a current pulse with a duration of several microseconds. Among other characteristics of the HCVA plasma, the angular distribution of ions of various types at distances of several centimeters was obtained. This distribution can be directly measured in an experiment to test the model approaches.

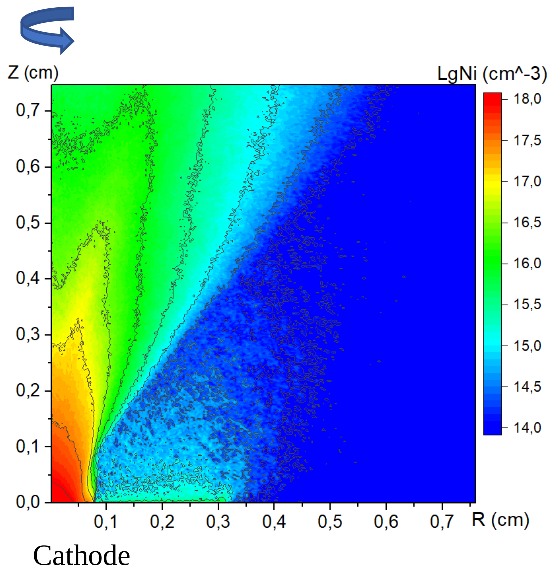

Fig.1. Example of HCVA plasma density distribution.

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KINETIC SIMULATION OF A PLASMA JET ORIGINATED FROM A CATHODE SPOT

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The emergence and subsequent expansion of the plasma from the cathode spot is a necessary component of the functioning of the vacuum arc [1]. New results of two-dimensional kinetic modeling of plasma expansion from a cathode spot are presented. The simulation was carried out using the Particle-in-Cell electrostatic method, taking into account the reactions of ionization and recombination of particles by the Monte Carlo method. The Coulomb interaction of charged particles was taken into account within the framework of the Takizuka&Abe binary method. Plasma expansion from the cathode spot is almost spherically symmetrical, with emerging a large density gradient (Fig. 1). To resolve this gradient by the particle method, a system of nested structured grids was used, which made it possible to significantly reduce the number of required macroparticles while maintaining acceptable accuracy.

During the simulation, it was shown that the current that can pass the cathode spot with the formation of a plasma jet expanding in an approximately self-similar mode is limited. Starting from a certain critical current, instability arises in the jet plasma, leading to plasma decay and subsequent blocking of the current flow. This is probably one of the mechanisms that determine the maximum current per one cathode spot in a vacuum arc.

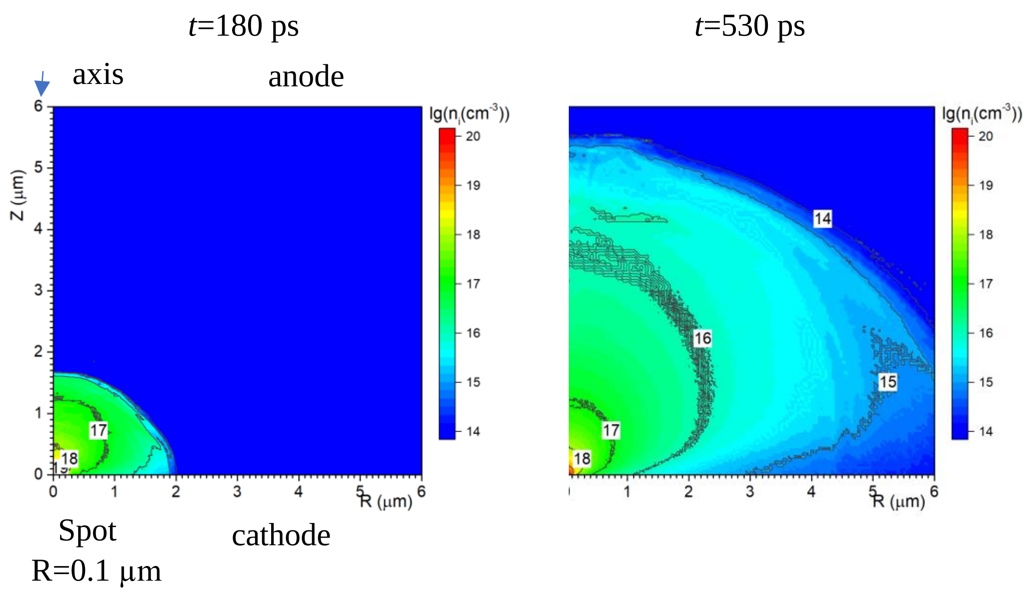

Fig.1. Plasma density at different instants. Current 0.125 A.

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NUMERICAL MODEL OF A GASEOUS INDUCTIVE DISCHARGE IN OXYGEN, TAKING INTO ACCOUNT THE COMPLETE SCHEME OF THE VIBRATIONAL KINETICS OF O2 MOLECULES*

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Non-equilibrium low-temperature oxygen plasma has a wide range of applications. The use of such plasma has literally revolutionized many industrial processes such as plasma etching, surface treatment, plasma sterilization and medicine. The study of vibrational excitation and relaxation in oxygen plasma is poorly studied area due to the complexity of experimental methods for detecting the vibrational distribution function in oxygen. New experimental data on the distribution of vibrational excitation in stationary and nonstationary discharges in oxygen was recently obtained [1] and this indicates the need to develop more accurate models to describe the relaxation kinetics of vibrational excitation under conditions of significant gas dissociation and to adapt these processes into complete self-consistent models.

Based on previous work [2,3], a two-dimensional hydrodynamic model was built for a discharge in oxygen. In addition to equations for describing the kinetics of charged particles, the model includes a detailed scheme of plasma-chemical reactions and equations for the temperature and neutral gas flow. Accounting for gas heating is especially important when studying processes in mixtures containing molecular gases [4].

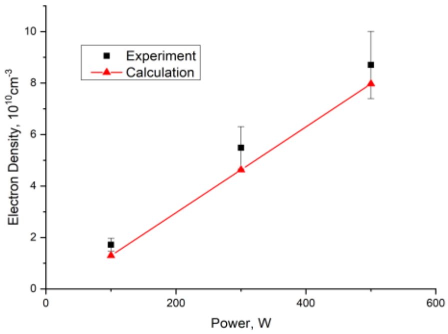

Fig.1. Comparison of the calculated electron density with experimental data.

The resulting model was tested against theoretical and experimental data in a simple cylindrical chamber from [5]. The concentrations of electrons (see Figure 1), ions and oxygen atoms, as well as electron and gas temperatures were compared depending on the power deposited in the discharge.

To verify the developed model of kinetics, with VV/VT processes involving O_2(v) molecules and the processes of VT relaxation on O atoms on experimental data [1], it was integrated into a two-dimensional hydrodynamic model of an ICP. The vibrational distribution function was calculated in low-pressure ICP as well as spatial distributions of plasma parameters (density and temperature of electrons, excited components, neutral gas temperature, etc.), and flows of charged and active neutral particles at the reactor walls.

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NUMERICAL ANALYSIS OF RUNAWAY ELECTRON BEAM FOCUSING WITH A HOMOGENEOUS LONGITUDINAL MAGNETIC FIELD

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One of the main issues limiting a technical usage of the runaway electron (RE) phenomenon is a low current density of a RE beam generated in a pulsed gas discharge of high pressure. Recently, pioneer experimental research on the RE beam focusing with a longitudinal magnetic field has been carried out [1]. Employing the guiding magnetic field with an induction of up to 4 T has allowed the research group to achieve the record high value of the RE beam current density of 0.65 kA/cm^2. However, the theoretical analysis of the problem is complicated by the necessity of simultaneous consideration of the RE beam interaction with both magnetic and electric fields and gas particles. Therefore, many aspects of the RE beam focusing process has been out of the research scope [1]. In particular, it is hard to predict an optimal configuration of a discharge gap to obtain a maximum possible current density value.

The present work is devoted to the numerical investigation of focusing the RE beam with the longitudinal magnetic field of various induction. The 3D Monte-Carlo numerical model was developed. The model took into account the acceleration of electrons with an electric field, their interaction with the magnetic field, and the electron scattering on gas particles. The gas considered was nitrogen under a pressure of 1 atm. The collision module operated with a set of 17 electron-molecular scattering processes. The source data were total, differential and double differential cross-sections for respective scattering processes (including elastic scattering, ionization, excitation of rotational, vibrational and electronic states of the nitrogen molecule) [2-4]. The collision module is described in detail in [5]. The problem geometry considered was the same as in the experimental work [1]: a cone-shaped cathode and a flat anode. The longitudinal magnetic field was assumed to be homogeneous. As a result of the simulation, the dependence of the RE beam diameter on the magnetic field induction value was obtained. It was compared with the one obtained in [1]. It was found that the simulation results were in a good agreement with the experimental study. In addition, the electron trajectory analysis allowed distinguishing two types of the electron motion across the discharge gap: the collisional mode and the magnetized mode. Conditions of the electron motion transition from the collisional mode into the magnetized mode were determined.

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SIMULATION OF ELECTRON FOCUSING BY ANODE MICROPROTRUSIONS IN GAS DISCHARGES OF HIGH PRESSURE

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To initiate a pulsed gas discharge of a high pressure, it is a common practice to use a discharge gap producing a strongly inhomogeneous electric field distribution, e.g., a tip – plane electrode system. Usually, a tip-shaped electrode is a cathode and a flat electrode is an anode. Because of extremely high electric field magnitude at the apex of the tip, a lot of explosive emission craters appear on the cathode after every single high voltage pulse due to the transition of a field emission process into an explosive one. However, within the work [1], it was experimentally observed, that explosive emission craters may appear on a tip-shaped electrode surface even when this electrode is an anode, not cathode. In this case, the transition of the field emission into the explosive one was impossible due to an inverse polarity of the voltage applied. So, there must be some other mechanism of the crater formation. The possible mechanisms are: 1) charge and subsequent explosion of dielectric pollutions on the tip surface; 2) focusing fast electrons by microprotrusions on the tip surface, heating up of the microprotrusions and their explosion.

The present paper is devoted to testing the second possible mechanism of the anode crater formation within pulsed gas discharges of high pressure. With a help of a numerical 2D Monte-Carlo model developed, focusing electrons by a cone-shaped microprotrusion located on the tip-shaped anode surface was considered within *R-Z* cylindrical geometry. A base of the cone was 5 μm, a cone height was 10 μm. For the sake of calculation simplicity, a relatively small area near the microprotrusion, where the electric field enhancement factor was significantly more than 1, was considered. The outer border of the computational domain was at the distance of 30 μm from the microprotrusion apex. Since the radius of the anode tip was assumed to be much larger that the microprotrusion size, so the electric field at the distance of 30 μm from the cone apex was set to be almost homogeneous. An electric field configuration near the microprotrusion was calculated with a help of the ANSYS software package. The microprotrusion was assumed to have a positive potential respective to the outer boundary. The voltage applied to the computational domain was varied from 200 V up to 4000 V, the associated homogeneous field strength (without taking into account the enhancement factor) near the microprotrusion was varied from 50 kV/cm up to 1 MV/cm.

From the outer boundary of the computational domain, an initially uniform flow of electrons with given initial energy was assumed to be injected towards the microprotrusion. An initial current density of the flow was constant. Employing the Monte-Carlo model, the electron drift towards the microprotrusion was calculated. During the simulation, electron scattering on the gas particles (nitrogen, 1 atm) was considered. For the collisions to be simulated properly, data set on the total, differential and double differential cross sections of the electron-molecular interaction processes was used [2-4]. The collision model is described in detail in [5]. As the result of the simulation, the optimal relation between the field near the microprotrusion and the electron initial energy to achieve a maximum growth of the electron current density at the apex of the microprotrusion was found. In addition, the energy distributions of electrons having reached the anode (the microprotrusion) were obtained. Employing the data of the simulation, the criterion of the microprotrusion explosion was determined.

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G1-P-006601

INVESTIGATION OF CHANGES IN THE FIELD EMISSION CHARACTERISTICS OF THE ERODED CATHODE SURFACE AFTER SUBMICROSECOND VACUUM ARC DISCHARGES WITH DIFFERENT CURRENT AMPLITUDES

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In the course of this study, a multifactorial investigation of the influence of the parameters of a vacuum discharge on the copper cathode on its emission properties was carried out. The object of the study was the surface of copper cathodes obtained by melting the tips of copper needles in vacuum. Thus, spherical tips of cathodes with an initially smooth surface served as the base emitters. The typical radius of the cathode tip was 25-50 μm.

The experiments were carried out under high vacuum conditions. Several cathodes were subjected to vacuum arc discharges of submicrosecond duration with a current amplitude in the range of tens of amperes. After each discharge, the cathode was placed in a field-emission projector inside the same vacuum chamber without breaking the vacuum conditions. The distribution of the emitting regions over the sample surface was estimated via the projector. An automated measuring system was connected to the projector to obtain the voltage-current characteristics of the field emission. The system allowed measurements in ranges of voltage up to 30 kV and current from 1 nA to 3 μA. According to the voltage-current characteristics, the factor of the electric field enhancement on the surface of the emitter was estimated.

G1-P-006602

INVESTIGATION OF COPPER CATHODE SURFACE CONDITIONING BY SUBNANOSECOND VACUUM DISCHARGES

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A copper needle cathode with a tip radius of about 35 μm was subjected to several vacuum arc discharges of submicrosecond duration, which led to significant erosion of the surface and a change in its microrelief. This cathode was then connected to a RADAN pulse generator with a pulse duration of less than 1 ns. Several hundred vacuum discharges were performed on this setup.

Before and after the treatment with subnanosecond pulses, the emission characteristics of the sample and the state of its surface were studied. Emission characteristics were studied on a field-emission projector with an automated measuring complex to obtain voltage-current characteristics of the field-emission. The results of these measurements made it possible to estimate the electric field enhancement factor on the sample. The microrelief of the sample surface was studied by scanning electron microscopy. A significant decrease in the field enhancement factor and a decrease in the characteristic dimensions of the surface microrelief elements were shown.

G1-P-007501

ELECTROTECHNICAL CALCULATION OF THE CURRENT DISTRIBUTION UNDER FOIL ELECTRICAL EXPLOSION

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We present the results of 2D simulations of the aluminium plate heated and aluminium foil electrically exploded under the action of current pulse (formed by capacitor bank discharge). The plate (foil) and the return conductor are replaced by an elementary conductors. The differential equation system for inductively coupled elementary circuits, formed by the plate (foil) and return conductor is considered. Due to nonuniform current density distribution over the plate (foil) cross section (owing to the skin and proximity effects), the plate heating and foil electrical explosion occur nonuniformly.

MEASUREMENTS OF VACUUM ARC THRESHOLD CURRENT FOR W AND CU CATHODE

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The threshold current is a statistical value that shows the minimum current needed to self-maintain one cell of the cathode spot. Its value is necessary for constructing a physical model, and therefore for understanding the processes in the cathode spot of the vacuum arc. A detailed study of the threshold current for a number of cathode materials was carried out by Kesaev [1]. However, its results need to be clarified for several reasons. Firstly, for refractory metals, measurements were performed under atmospheric conditions. Which casts doubt on the purity of the metal surface. Secondly, it is necessary to increase the time resolution, since the lifetime of the current cell is dozens of ns. Thirdly, Kesaev used the method of opening contacts to initialize the arc.

It is proposed to conduct experiments in a vacuum chamber at a pressure not worse than 10^{-8} torr. To clean the surface of the electrodes, heating to high temperatures, arc discharge and vacuum remelting can be applied. Use a low inductance shunt and a 1 GHz bandwidth oscilloscope to measure ns processes. A high-voltage pulse of 20 kV, 500 ns can be used to initialize the arc.

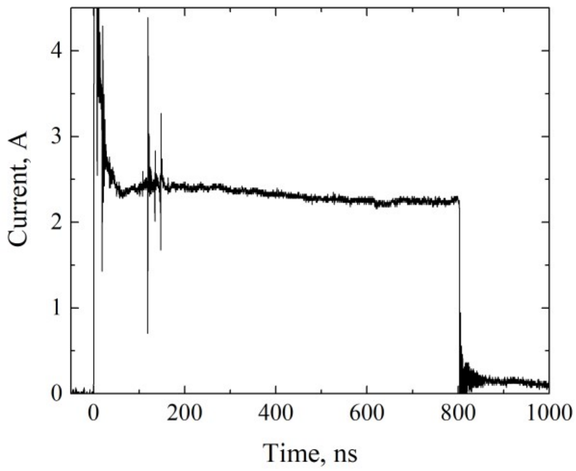

Fig.1. Waveform example of the arc current.

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INVESTIGATION OF TRANSIENT PROCESSES IN AN ARC DISCHARGE WITH A SHARP CHANGE IN SUPPLY VOLTAGE

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The transient processes of a vacuum-arc discharge with tungsten and copper electrodes were studied. A multichannel cable generator was used as a discharge voltage source. The generator made it possible to obtain pulses with a duration from 45 ns to 1.3 μs. The main feature of the generator is the ability to obtain rectangular pulses with a front duration of up to 3 nanoseconds. The supply voltage was obtained by merging two pulses with a delay. The result was a “stepped” pulse (Fig.1). The discharge current and plasma glow were studied. Data were obtained on the rate and shape of the response of the current and plasma glow both to a sharply increasing voltage and to a sharply decreasing voltage.

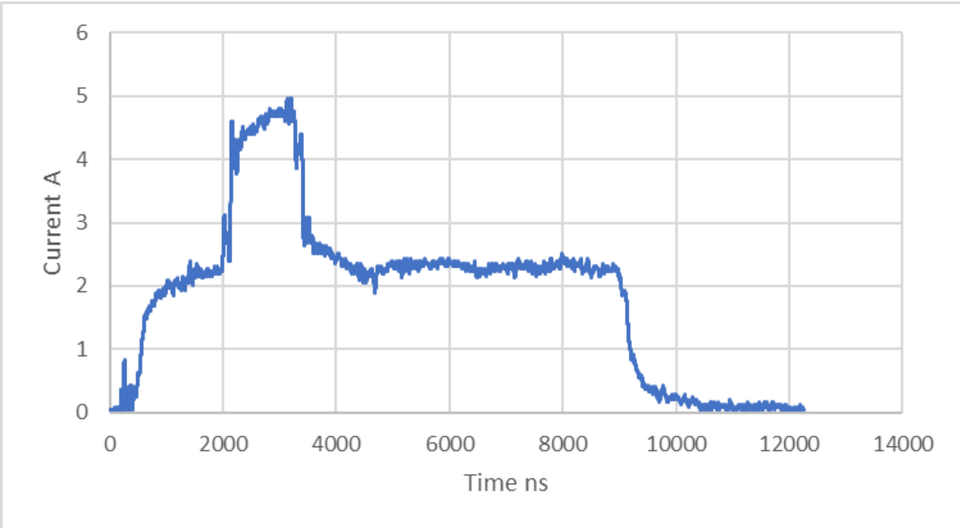

Fig.1. The “stepped” discharge current.

MODELING OF PREBREAKDOWN PHENOMENA IN THE CATHODE MICROPROTRUSION, TAKING INTO ACCOUNT THE HYDRODYNAMIC INSTABILITY*

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The explosion of the cathode microprotrusions due to heating by emission current is considered to be the basic mechanism of the vacuum DC [1,2] and RF [3-6] breakdown. However, in these approaches, the consideration of prebreakdown processes did not take into account the dynamics of the microprotrusion shape after melting. In this work the development of hydrodynamic and thermal instabilities after melting has been self-consistent simulated in a copper cathode microprotrusion exposed to DC electric field within the two-dimensional axisymmetric model. The model includes a self-consistent calculation of the electric field strength and emission characteristics within the PIC method, calculation of current density and temperature distributions in the microprotrusion. From the moment the melt appears in the top part of the microprotrusion, the model describes the movement of the liquid phase under the action of forces from the electric field (Maxwell stress) and surface tension forces. Within the framework of this model, modeling of the development of hydrodynamic and thermal instabilities for a microprotrusion with an initial electric field enhancement factor $\beta > 50$ was carried out. The dynamics of microprotrusion heating and the change in the microprotrusion shape after melting are shown in Fig. 1 and Fig. 2, respectively. Based on the obtained results, it is shown that the time for the development of thermal instability (explosion delay time) is significantly lower than in the case of an unchanged microprotrusion shape (see Fig. 1). This is due to the fact that after melting, the top of the microprotrusion in the electric field begins to stretch and become sharp (see Fig. 2). This leads to an increase in the electric field strength (electric field enhancement factor) and electron emission current density.

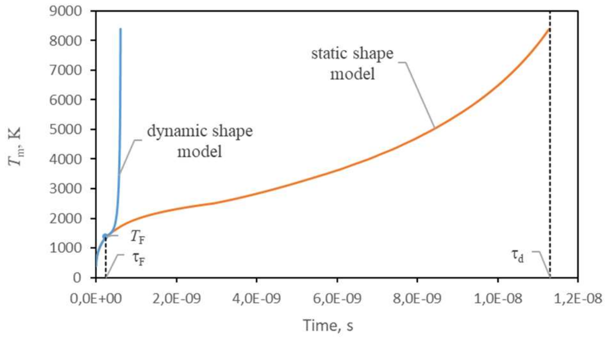

Fig. 1. Time dependence of the maximum temperature in a microprotrusion with $\beta \sim 62$ (E_{macro}= 225 MV/m) with an unchanged tip shape (red curve) and taking into account the development of electrohydrodynamic instability (blue curve).

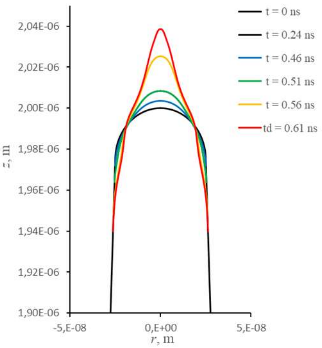

Fig. 2. Evolution of the profile of the top of a microprotrusion with $\beta \sim 62$ (E_{macro}= 225 MV/m) during the development of electrohydrodynamic instability.

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ELECTRIC EXPLOSION OF LIQUID METAL JETS UPON INTERACTION WITH THE CATHODE SPOT PLASMA 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 development of thermal and electrohydrodynamic instability in a liquid metal jet formed at the boundary of a cathode crater during melt splashing. The model includes a description of the interaction of the jet surface with the cathode spot plasma in the framework of the model of a collisionless space charge cathode sheet [2]. In the context of the proposed model, a self-consistent calculation of the hydrodynamics (see Fig. 1) and heating (see Fig. 2) of the jet has been simulated, taking into account the surface current and heat flux, assuming a quadratic decrease in the plasma concentration from the crater boundary. It is shown that at plasma concentrations > $8\cdot10^{19}$ cm^{-3} at the crater boundary, thermal instability develops in the jet, which leads to heating of the jet base region to the critical temperature. This process can be considered as a mechanism for initiating new cells of the vacuum arc cathode spot at the crater boundary.

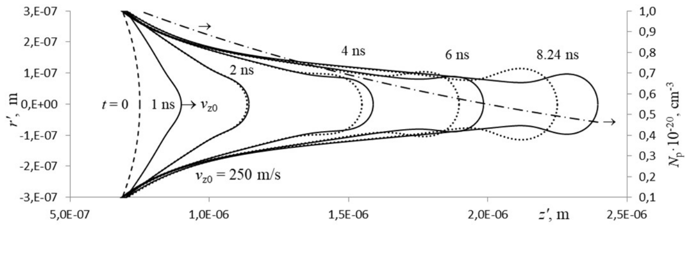

Fig. 1. Jet profile dynamics and plasma concentration distribution at $N_{p0} = 10^{20}$ cm^{-3} (right axis).
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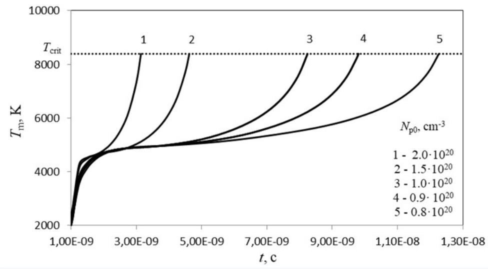

Fig. 2. Time dependence of the maximum temperature in the jet at different plasma concentrations at the crater boundary N_{p0}.

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STUDY OF THE HIGH-PRESSURE OPEN DISCHARGE*

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High-pressure discharges (up to atmospheric pressure of the working gas) with volumetric character of current flow are sources of nonequilibrium nonstationary plasma in high-energy gas-discharge devices.

The aim of the work was the investigation of the parameters of the "open" discharge at different pressures (up to atmospheric pressure) of the working gas - helium. The studies were carried out in a cuvette with a design similar to a planar kivotron with a drift space in the geometry: cathode - anode - drift space - anode - cathode), and operating in the mode of generation of counter propagating electron beams. Design dimensions of the cuvette: diameter of the working area of silicon carbide cathodes is 12 mm, distance cathode - grid anode - 3 mm, length of the drift space - 10 mm. The studies were carried out in a pulse train with a train frequency of 10 Hz with a filling frequency of pulses f = 95 kHz and voltage amplitude U = 2-35 kV with the duration of the voltage pulse edge $\tau \leq 2$ ns.

At gas pressure $p_{He} \approx 30$ Torr at U > 4-5 kV in the cathode-grid gap the discharge ignites and a homogeneous glow appears in the drift space, indicating the volumetric character of the discharge and propagation of the generated electron beam. When the pressure increases up to p = 1 atm the character of current flow does not change and remains volumetric. Typical oscillograms of the cell voltage and current through the cell at p = 100 (a) and 730 (b) Torr at f = 95kHz are shown in Fig. 1.c, and the dependence $j/p^2 = f(E/N)$ where j is the current density, E/N is the reduced electric field strength in a wide range of helium pressures p_{He} = 27-756 Torr and demonstrating the invariance of discharge parameters with pressure variation.

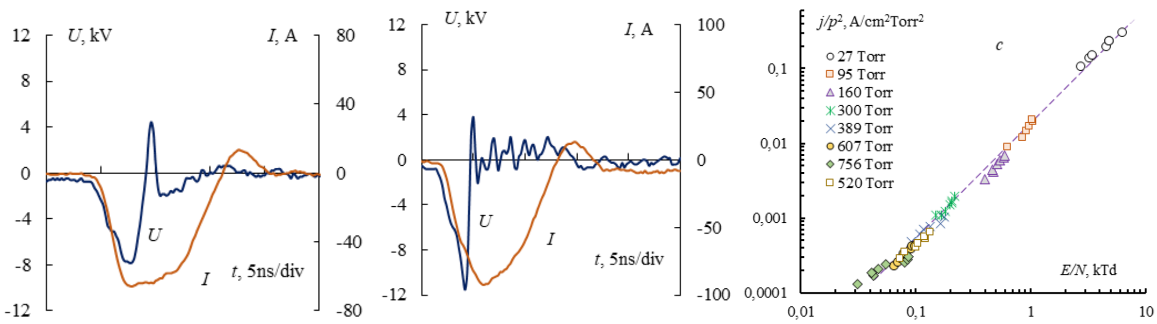

Fig.1. a,b - oscillograms of U, I at p = 100(a) and 730(b) Torr; c - dependences of j/p2(E/N) for different helium pressures..

* The work was supported in part by the RSF Grants No. 19-19-00069

INVESTIGATION OF ARC DISCHARGES DURING THE SYNTHESIS OF NANOSTRUCTURES

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The presented work is aimed at developing models of direct current arc discharges that describe in a unified way the processes occurring in the gas discharge gap and in the electrodes [1–3]. In particular, the work takes into account the effect of evaporation of the electrode material on the distribution of the main parameters of atmospheric pressure short arc plasma in inert gases: argon and helium with refractory (graphite) and non-refractory (copper) electrodes, the maintenance of the current in which is provided by thermionic emission and thermo-field emission, respectively.

In addition to plasma-chemical processes in the buffer inert gas - argon and helium for a discharge with graphite electrodes, a fairly detailed complex of plasma-chemical reactions was taken into account, taking into account the formation of neutral carbon particles C, C_2, C_3, their ions C^+, C_2^+, C_3^+ and excited states C*, C2*, C3*. For a discharge with copper electrodes, a set of elementary processes involving copper atoms taken from [4, 5] was taken into account.

Within the framework of one-dimensional geometry, the effect of evaporation of the electrode material on the characteristics of the arc discharge is numerically studied. The change in the plasma-forming gas is demonstrated by observing the transition from an arc discharge in an inert gas atmosphere (argon or helium) to an arc in vapors of material evaporating from the electrodes.

It should be noted that in the dependences of the voltage on the current density, as well as the concentrations of charged and neutral plasma particles averaged over the discharge gap in inert helium, there is a jump in the potential drop. This jump is due to the intense evaporation of the electrode material - carbon or copper, the ionization potential and impact ionization cross sections of which are much lower than the corresponding parameters in helium.

It should be noted that in an arc discharge the characteristics are monotonic depending on the current density. The results obtained were compared with the available experimental and numerical data from the literature [4, 6].

The results obtained formed the basis for the development of modern miniature plasma-chemical reactors for the synthesis of nanostructures.

The study was carried out with the financial support of the Russian Science Foundation and the Cabinet of Ministers of the Republic of Tatarstan within the framework of the scientific project No. 22-22-20099.

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FEATURES OF ELECTRON RUNAWAY IN A GAS DIODE WITH A NEEDLE CATHODE*

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In a sufficiently strong electric field, free electrons in the gas medium begin to accelerate continuously, i.e. transit into the runaway mode [1,2]. Runaway electrons (RAEs), generated when a voltage pulse with an amplitude of tens to hundreds of kilovolts is applied to a centimeter-scale gas gap, cross it at speeds comparable to the speed of light and preionize the gas, thereby determining the dynamics of its subnanosecond breakdown [3–5].

In the present work, we study the conditions of electron runaway in a gas diode with a needle cathode. It is shown that runaway conditions are qualitatively different for needles with relatively large and small tip radii R, i.e., in fact, for different degrees of electric field inhomogeneity. This difference leads to a nonmonotonic dependence of the threshold runaway voltage U_c on the tip radius R (see Figure 1). It has a minimum at $R_c \approx 475\,\mu\text{m}$, where the character of the runaway changes. At $R > R_c$, i.e. for a weakly inhomogeneous field, the transition of electrons to the runaway mode is determined by the local distribution of the field near the place where they start (the tip of the needle). If the field strength near the cathode exceeds the critical value E_c, which depends on the type of gas and its pressure, then the electron will be continuously accelerated throughout the gap. At $R < R_c$, i.e. for a strongly inhomogeneous field, the runaway condition takes on a nonlocal character. As the distance from the cathode increases, the braking force acting on an electron in the gas grows, and the electron that has transferred into the runaway mode near the cathode can begin to decelerate and become thermal at the periphery. In this case, the behavior of the electron near the anode will define the runaway threshold. The threshold voltage is determined from the requirement that the electron energy reaches its maximum at the anode, and, for its calculation, it is necessary to take into account the entire history of the RAE motion in the interelectrode gap.

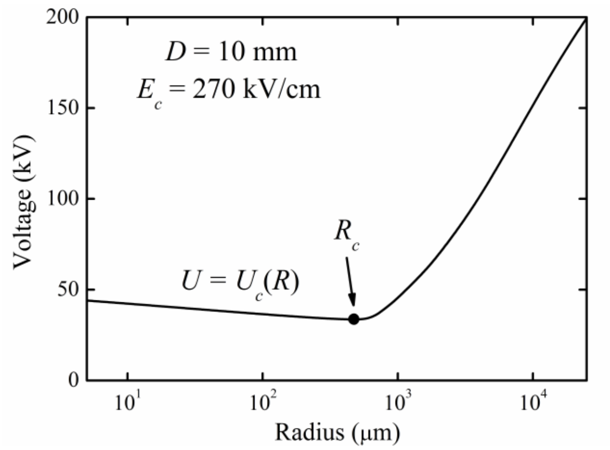

Fig. 1. Numerically calculated dependence of the threshold runaway voltage U_c on the needle tip radius R (the interelectrode distance is D = 10 mm, the gas is atmospheric air). The dot shows the minimum of this dependence, which falls on the radius $R_c \approx 475\,\mu\text{m}$.

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G1-P-011801

THE DISCHARGE WITH CONTROLLED INHOMOGENEITY FOR EXCIMER LASERS PUMPING

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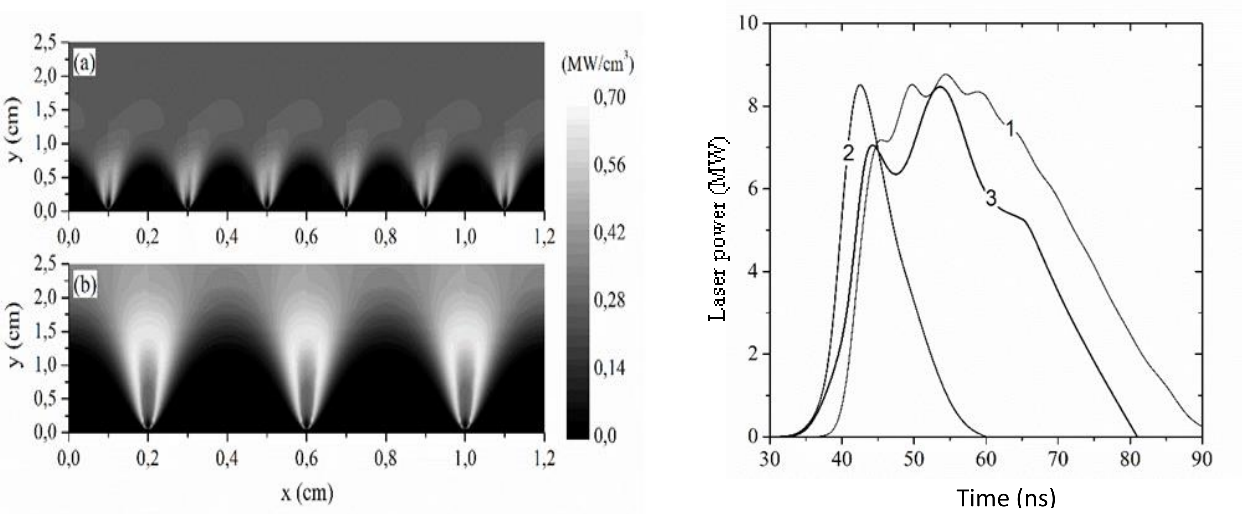
The instability of pump discharges with an increase in their specific power to the development of current inhomogeneities is the main problem of electric-discharge excimer lasers. However, as was shown in [1], under certain conditions, the forced inhomogeneity of the discharge can be used to increase the local specific pump power in the discharge volume in excimer mixtures.

The report presents the results of numerical simulation of the operation of a KrF-laser with an inhomogeneous pump discharge on a mixture $Ne/Kr/F_2$. An analogue of cathode spots were extended blades on the cathode surface. The effect of the density of cathode spots on the energy and duration of the lasing pulse is discussed. (Fig. 1). It is shown that with an increase in the density of current channels, the duration of the diffuse stage of discharge burning and the volume of the active medium increase, but the possibility of a local increase in the pump power decreases. In general, the required degree of discharge inhomogeneity depends on the capabilities of the exitation circuit, which determines the total power delivered to the discharge.

In addition, based on 0D calculations, the values of the optimal specific pump power for KrF, KrCl, and ArF lasers were obtained. It is shown that in regions with a higher power density, a high rate of quenching of excimer molecules by electrons leads to the degradation of laser radiation.



(a) (b)

Fig.1. The distribution of laser power density over the discharge cross section for the S_{el}/S_k ratio: 0.1 – a, 0.05 – b. Here S_{el} is the total area of the electrode; S_k is the area of the cathode occupied by the discharge (a). Laser radiation power for: the homogeneous discharge – 1, the Sel/Sk ratio is 0.05 – 2, the Sel/Sk ratio is 0.1 – 3 (b).

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KINETIC MODEL OF PLASMA GENERATED BY THE FLOW OF PRIMARY ELECTRONS

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At low pressure plasma can be formed due to the capture of ions in the potential well created by primary electrons [1]. The purpose of this work is to develop a kinetic model of the plasma

Neglecting the concentration of secondary electrons we assume that the concentration of primary electrons n_1 is the same throughout the gap with length $2L$. To describe ions we use the kinetic equation with the τ - approximation collision integral

$$v_x \frac{\partial F}{\partial x} - \frac{e}{M}\frac{d\varphi}{dx}\frac{\partial F}{\partial v_x} = \nu_i n_1 f_m(v_x) - \frac{F - F_0}{\tau} \tag{1}$$

where v_x - velocity, F - distribution function, x – coordinate, e – elementary charge, M – mass of ion, φ - potential, ν_i – frequency of ionization, F_0 – equilibrium distribution function, τ - effective collision time, $f_m(v_x) = \left(M/2\pi kT\right)^{1/2}\exp(-Mv_x^{\,2}/2kT)$ - Maxwellian distribution.

Neglecting the weak electric field in the plasma, we assume that the entire potential drop φ_w is concentrated in a narrow electrode sheath. Under these conditions $F_0 = n_0 f_m(v_x)$ and the kinetic equation has the following solution

$$F(x,v_x) = \begin{cases} (\tau\nu_i n_1 + n_0)\, f_m(v_x), |v_x| < \sqrt{2e\varphi_w/M} \\ (\tau\nu_i n_1 + n_0)\, f_m(v_x)\left(1 - \exp\left(-\dfrac{(x+L)}{\tau v_x}\right)\right), v_x > \sqrt{2e\varphi_w/M} \\ (\tau\nu_i n_1 + n_0)\, f_m(v_x)\left(1 - \exp\left(-\dfrac{(x-L)}{\tau v_x}\right)\right), v_x < -\sqrt{2e\varphi_w/M} \end{cases} \tag{2}$$

When the condition $\tau\sqrt{2e\varphi_w/M} >> L$ is satisfied, the probability of collisions for outgoing particles is negligibly small. In this case simpler expressions can be obtained

$$F(x,v_x) = \begin{cases} (\tau\nu_i n_1 + n_0)\, f_m(v_x)\left(\dfrac{x+L}{\tau v_x}\right), v_x > \sqrt{2e\varphi_w/M} \\ (\tau\nu_i n_1 + n_0)\, f_m(v_x)\dfrac{(x-L)}{\tau v_x}, v_x < -\sqrt{2e\varphi_w/M} \end{cases} \tag{3}$$

Taking into account that the ion current density is equal to $\nu_i n_1 x$ and using the quasi-neutrality condition, one can obtain the following formula relating the ionization frequency and the depth of the potential well

$$\nu_i = \frac{1 - erf(\sqrt{e\varphi_w/kT})}{\tau\left(erf(\sqrt{e\varphi_w/kT}) + \dfrac{L}{\tau\sqrt{2\pi kT/M}} E_1\left(\dfrac{e\varphi_w}{kT}\right)\right)}, \tag{4}$$

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G1-P-014402

MODEL OF PLASMA OF LOW-PRESSURE DISCHARGE IN MAGNETIC FIELD

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Consider the problem in plane geometry. We assume that the cathode is located in the x=0 plane, and the anode of the discharge system is located in the x=L plane. A magnetic field with induction B is applied to the gap. The influence of the magnetic field on the motion of ions with a large mass can be neglected. In addition, it can be assumed that at low pressure the ions leave the gap without collisions. Then, in the cold ion approximation [1], the equation of motion can be written in the following form

$$M\,\frac{d(n_i v_i^2)}{dx} = e n_i E \tag{1}$$

where n_i and v_i are the concentration and average velocity of ions, M is the ion mass, E is the electric field strength, e is the elementary charge. As for electrons, they, as a rule, are magnetized in the considered discharges and we write the following expression for the density of the electron flux,

$$n_e v_e = -D_e \frac{dn_e}{dx} - \mu_e n_e E \tag{2}$$

where n_e, v_e, D_e and μ_e are the concentration, the average speed of directional movement, the diffusion coefficient and the mobility coefficient of electrons in a transverse magnetic field. We assume that ionization occurs uniformly throughout the gap and introduce parameter A defined by the following expression

$$A = \frac{m\omega^2 L}{4\nu\sqrt{kT_e M}} \tag{3}$$

where m is the electron mass, ν is the collision frequency, ω=eB/m is the Larmor frequency k is the Boltzmann constant, T_e is the electron temperature.

Using the quasi-neutrality condition n_e = n_i we have obtained the following expressions for the plasma concentration

$$\begin{gathered}\frac{n}{n_0} = 1 - A\left(\frac{x}{L}\right)^2 + \sqrt{\left(1 - A\left(\frac{x}{L}\right)^2\right)^2 - \left(\left(\frac{x}{L}\right) - 1\right)^2},\ A > 1 \\ \frac{n}{n(0)} = 1 - \frac{2A}{1+A}\frac{x^2}{L^2} + \sqrt{\left(1 - \frac{2A}{1+A}\frac{x^2}{L^2}\right)^2 - \left(1 - \frac{2x}{(1+A)L}\right)^2},\ A < 1\end{gathered}\ , \tag{4}$$

The discharge structure with a positive anode fall is formed at A>1, and the anode fall is negative at A<1. When A=1, the anode sheath is absent and the plasma is in contact with the anode surface.

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EXPERIMENTAL RESEACH AND END-TO-END SIMULATION OF THE MINIATURE LINEAR ACCELERATOR

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A miniature linear accelerator (MLA) can be conditionally divided into three main elements: ion source (IS), an ion-optical system (IOS) and a neutron-generating target, assembled in a sealed case [1]. Traditionally, one of the main types of IS used to create MLA is a penning type ion source. In 1937 F.M. Penning and J.H. Moubis proposed for first time to use the discharge in crossed *ExH* fields in ions sources for implementation of nuclear D-D reaction and neutron production [2].

In this paper, an experimental study of a miniature linear accelerator with penning ion sources was done. Experimental equipment and measurement methods are described in detail in [3]. The MLA operating characteristics are determined – the current waveforms amplitude-time characteristics (discharge and extraction currents) are measured. The neutron flux and the extraction current dependences on the discharge current at various accelerating voltage are obtained. The paper also considers end-to-end simulation MLA by PIC (Particle-In-Cell) with MCC (Monte-Carlo Calculation) implemented in the Tech-X VSim 9.0 software [4]. Firstly, gas discharge in the penning ion source is simulated and its quasi stationary mode is determined. Second stage: a) charge particles motion calculation in ion-optical system (IOS) MLA (taking into account kinetic processes), b) sputtering of MLA elements, c) thermal desorption of hydrogen ions under the ion radiation influence. The simulation final result is to obtain neutron yield on time and the neutron on target current dependences, as well as validation with experimental data.

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BIPOLAR MIXED ARC AND HIPIMS MODE DEPOSITION OF CARBON COATINGS ON FLOATING SUBSTRATE*

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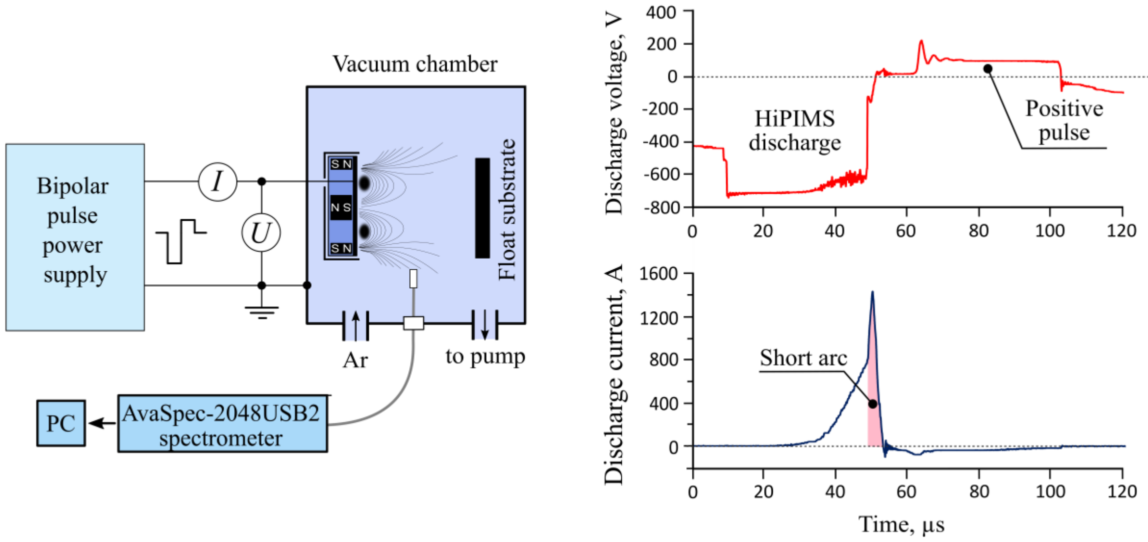
The paper describes a new carbon coating deposition process (bipolar mixed mode), which combines two technologies - bipolar high-power impulse magnetron sputtering (HiPIMS) [1, 2] and a mixed mode of cathodic arc – sputtering process [3,4]. Bipolar mixed mode is implemented on the basis of an unbalanced magnetron and a specially designed pulsed power supply (Fig. 1.a). As a result of the formation of a high-power magnetron discharge pulse on a graphite target, a short arc is initiated, after which a positive polarity pulse is applied to the target. The shapes of the discharge voltage and current pulses are shown by the oscillograms in fig. 1.b. Sputtering and ionization of carbon atoms occurs during a high power pulse of magnetron and arc discharges. The positive pulse is used to accelerate the ions towards the substrate. Such combination makes it possible to generate a large number of carbon ions and manage their energy in order to bombard the floating substrate. The arc pulse amplitude exceeds 1 kA with a duration of several microseconds and a frequency of several hundred Hz. In addition to bipolar mixed mode, the paper presents other magnetron sputtering modes, namely mixed mode without positive pulse, bipolar and unipolar HiPIMS modes. The results of measurements of the discharge electrical parameters and optical emission from the plasma are presented. In the abovesaid modes, carbon coatings are obtained and their characteristics (composition, hardness and wear resistance) are studied.



(a) (b)

Fig.1. (a) Scheme of the experimental setup and (b) oscillograms of discharge voltage and current pulses in bipolar mixed mode sputtering of carbon.

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LASER PLASMA EMISSION CHARACTERS IN SOFT X-RAY AND EUV SPECTRAL RANGE

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Nowadays area of using roentgen optics is activity developing in different spheres, such as roentgen lithography, microscopy or reflectometry. In this spheres different radiation sources can be used, but laser-plasma sources [1] became more used. Effective generation of soft X-ray and EUV radiation needs laser radiation high power and good absorbing dense target. Solid is more investigated target, but one of solid target characteristics is more optics system pollution. Gas-jet and liquid-jet targets often don`t have this problem, but those are less investigated.

So, the research purpose is investigating of emission specters and absolute radiation values of different gas-jet and liquid-jet targets in 20-200 A spectral range.

For investigate used special developed installation, which allow to take spectral measurements of laser plasma. The installation feature is using cryogen pumps, allowing to make effective pumping of gas-jet and liquid-jet targets with keeping pressure by 10^{-2} Pa in the camera. Pulse and statics formation systems of different constructions targets were used. Nd:YAG laser with wave length 1024 nm, pulse energy ~0.8 J, pulse duration 5.2 ns was used for target ionization. Spectral measurements were taken by using instruments RSM-500 and reflection spectrometer by multilayered roentgen mirror. The installation is describing in details in [2, 3].

In results of research specters of inert gases Ne, Ar, Kr, Xe and molecule gases N2, CO2, CHF3, SF6 were investigated. Also specters of liquid, such as alcohols, cyclohexane and different halogen hydrocarbons were investigated. For all those materials absolute emission values were defined for a row of lines. By obtained results developing radiation sources for industrial applications.

The research is supporting by RFBR, grants № 22-62-00068.

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G2-O-002901

RIBBON ELECTRON BEAM SOURCE OPERATING IN A WIDE PRESSURE RANGE

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Low-temperature nonequilibrium plasma formed during the passage of an accelerated electron beam through a gas [1, 2] is used to affect the surface of various materials of nanoelectronics, medicine, as well as in the study of processes in a thermonuclear reactor [2]. Plasma parameters depend on the current and energy of the beam electrons, as well as due to changes in the type and pressure of the gas in the working volume of the vacuum chamber. The volume of plasma determines its ability to process large-area objects. To generate beam plasma in a large volume, it is reasonable to use a wide-aperture electron beam, in particular a ribbon beam [3]. The required operating pressure range from 0.01 to 10 Pa can be achieved by combining several discharge systems. In this paper, a ribbon electron beam source consisting of a main and an auxiliary discharge system is presented. The aim of the work is to study the features of electron beam generation in a wide range of pressures by a source based on a two–cathode discharge system.

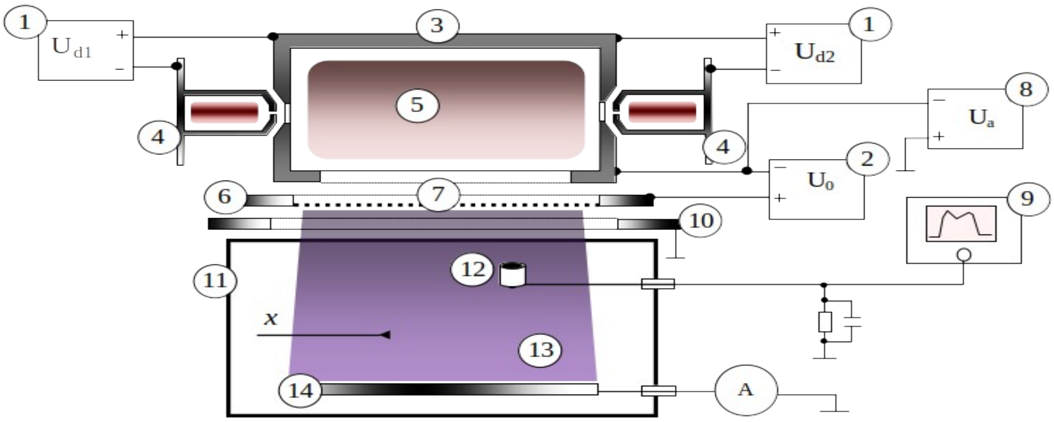

Figure 1 – Diagram of the source and measurement of its parameters. 1 – Auxiliary discharge power supply, 2 – main discharge power supply, 3 – hollow anode, 4 – hollow cathode of auxiliary discharge, 5 – plasma of the main discharge, 6 – flat anode of the main discharge, 7 – emission grid, 8 – accelerating voltage unit, 9 – oscilloscope, 10 – accelerating electrode, 11 – vacuum chamber, 12 – current collector or Langmuir probe, 13 – electron beam, 14 – electron beam collector.

As a result of the study, the modes of operation of the source at low (0.01 Pa) and high (10 Pa) pressures, the dependences of the uniformity of the current density during the transition from one operating pressure to another were obtained.

The work was supported by a grant of the Ministry of Higher Education and Science, FEWM-2023-0012

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G2-O-003102

LOW-PRESSURE HIGH-CURRENT PULSED MAGNETRON DISCHARGE WITH ELECTRON INJECTION FROM VACUUM ARC

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The results of deposition of copper films in argon in a range of ultra-low (up to 0.03 Pa) operating pressure with use of a pulsed-periodic (10÷25 pps, 250÷1000 µs) high-current (10÷30 A) planar magnetron discharge with electron injection are presented. The injection of electrons into the cathode layer of the magnetron discharge was carried out from the back of the target through the central aperture (2 mm). The plasma of a vacuum arc discharge was used as an electron emitter. The use of the vacuum arc discharge as electron emitter is due to the possibility of its operation without additional gas supply. The current of the vacuum arc was varied in a range of 10÷20 A. Contamination of magnetron plasma and substrate by macroparticles fraction from the emitter was prevented by the geometry of the discharge system, as well as by the reflector electrode installed directly behind the output aperture. Injection of additional high-energy electrons with a current of few amperes provided a shift of the operating pressure range of the magnetron discharge to the lower pressure values. Increase of a burning voltage of magnetron in the low pressure range provides a large fraction of the metal ions component in magnetron plasma and a large energy of sputtered atoms. The last occurs also due to a decrease in thermalization of atoms in the drift space by reducing the number of collisions at operating pressure decrease.

It has been experimentally shown that films obtained at a lower operating pressure are characterized by a decrease in surface roughness, an increase in the crystallinity degree and a decrease in the grain size of crystallites. In the range of ultra-low operating pressure at a fixed voltage of magnetron discharge, the increase of injected electrons current and corresponding increase of magnetron plasma concentration provides an increase in the deposition rate (Fig.1) and the density of the formed copper films.

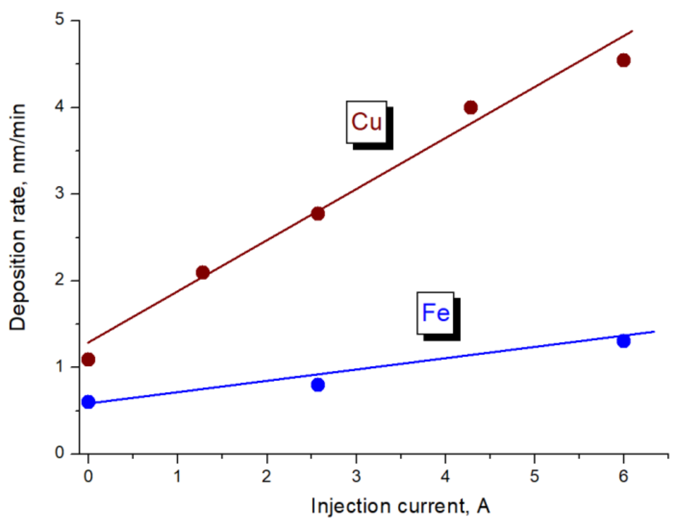

Fig.1. Deposition rate versus injected electrons current.
Magnetron discharge voltage for copper (Cu) target is 380 V, for iron (Fe) target is 660 V.

This work was supported by the Russian Science Foundation, project # 21-19-00136.

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COMPARATIVE STUDIES OF COLD PLASMA JET PARAMETERS UNDER DIFFERENT INITIATION CONDITIONS*

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Low-temperature atmospheric pressure plasma, particularly the cold plasma jet (CPJ), is a tool used for biomedical applications. CPJ is a sequence of streamers propagating into the environment in a flow of inert gas pumped through a discharge device. Plasma formation propagation is accompanied by generation of ions, nitrogen and oxygen radicals in the gas and water environment, actively interacting with cells of biological tissue. Published results of scientific research demonstrate, suppression of malignant tumors, caused by selective influence on healthy and cancer cells [1, 2]. However, a conditions variety of physical-biological experiments, including a variety of CPJ initiation ways, differences in plasma parameters at the surface of biological objects lead to difficulties in comparison and interpretation of research results.

The aim of this work was to compare the parameters of the CPJ generated in a helium He and argon Ar flow upon sinusoidal voltage excitation in a unified geometry of the discharge device for contact initiation method (CPJ_{CI}) and non-contact initiation method (CPJ_{NI}), most commonly used in biological experiments. The dependence of the current amplitude registered in the impact area with object on the applied voltage amplitude $I(U)$, was investigated. Particular attention was paid to the study of the frequency of the current touching the object f_I and the change in the current amplitude depending on the applied voltage frequency $I(f_U)$ in the range of f_U = 10-50 kHz (Fig. 1). It is found that for CPJ_{CI} generated in the He flow, there are conditions in which the frequency of the current touching the object f_I differs from the f_U, and can be a multiple of 4 ($f_U = f_I/4$), a multiple of 2 ($f_U = f_I/2$) or equal to the frequency of the applied voltage ($f_U = f_I$). For CPJ_{NI} under similar conditions other ratios of f_U and f_I, characterized by a decrease in pulse amplitude, are defined. For CPJ_{CI} generated in Ar flow regular conditions of current touch frequency in the area of object impact ($f_U = f_I$) are observed in all modes of operation, however the current pulse amplitude increases by an order of magnitude, in comparison with helium CPJ_{CI}. In this work the object temperature in the area of CPJ influence at different modes of the device functioning was investigated and the modes of CPJ source functioning providing conditions of influence on living objects were determined.

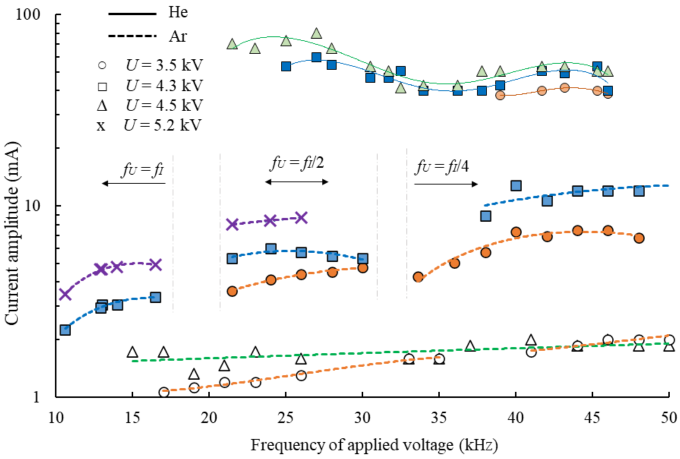

Fig.1. $I(f_U)$ dependences for the CPJ_{CI} (shaded symbols) and CPJ_{NI} modes (light symbols) in helium (dashed lines) and argon (solid lines). Расстояние до объекта 15 mm, υ = 9 l/min.

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ESTIMATION AND CALCULATION OF PARAMETERS OF GENERATION SYSTEMS OF BEAM-PLASMA FORMATIONS SYNTHESISED IN A HIGH-CURRENT NON-SELF-SUSTAINED GLOW DISCHARGE WITH HOLLOW CATHODE

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The report presents methods for estimation and calculation of parameters of BPF generation systems [1] for technological use and the creation of plasma emitters.

The main quantitative parameters that provide the required operational parameters and characteristics of the created plasma sources and electron-ion-plasma equipment as a whole are the concentration of gas-discharge plasma, as well as the ion current and electron current densities associated with it. It is convenient to calculate the systems for generating beam-plasma formations used for technological purposes of processing the surface of materials and products based on the required value of the current density of ions accelerated to the surface of the processed products or the current density of electrons extracted from the plasma formation and forming an electron beam.

Schemes and designs of experimental prototypes of systems for generating beam-plasma formations (BPF) based on a high-current non-self-sustained glow discharge with a low-pressure hollow cathode, calculated and created on the basis of the methods presented in the report, are described.

The work was carried out within the framework of the state task of the Ministry of Science and Higher Education of the Russian Federation on the topic No. FWRM-2022-0001.

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EFFECT OF CURRENT AMPLITUDE ON THE VELOCITY OF PLASMA FRONT PROPAGATION IN A HIGH-CURRENT DISCHARGE IN THE RAIL GEOMETRY OF ELECTRODES*

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In this work, we studied the current regimes of a plasma accelerator with a pulsed discharge between two long (L=30 cm) and parallel cylindrical electrodes 10 mm in diameter at two distances between the cylinders' axes h=30 and 22 mm. A high discharge current (up to 25 kA) was provided by a capacitor C = 1000 μF with a charging voltage U_0 up to 5 kV. The discharge was initiated locally at one end of the electrodes. Then the resulting plasma quickly moved to the exit and flew out of the accelerator at high speed. A high-current discharge was studied in nitrogen and helium at pressures varied from 4 to 50 Torr. The discharge regimes under study were with and without current spots (CS) on the electrodes. CSs appeared only in nitrogen at low plasma velocities (V < 5.0 km/s) and pressures exceeding 50 Torr. At lower pressures, there were no current spots in the discharge in helium and nitrogen. According to estimates, the current density in the CS does not exceed 10^6 A/cm^2. In the mode with CS, the anode CSs move along the electrodes together with the plasma continuously, and the cathode spots move in jumps, since the speed of their movement along the cathode is less than the speed of the anode CSs along the anode. This effect can affect the plasma velocity along the electrodes. In addition, in the absence of CS, the plasma leading edge, initially perpendicular to the direction of motion, inclines more and more toward the cathode with increasing velocity. Possibly, this effect is related to the lower velocity of discharge propagation along the cathode compared to its propagation along the anode. One of the reasons may be the finite time of the cathode layer establishment in the moving plasma. Thus, the study of cathodic processes in high-current plasma accelerators is of great interest.

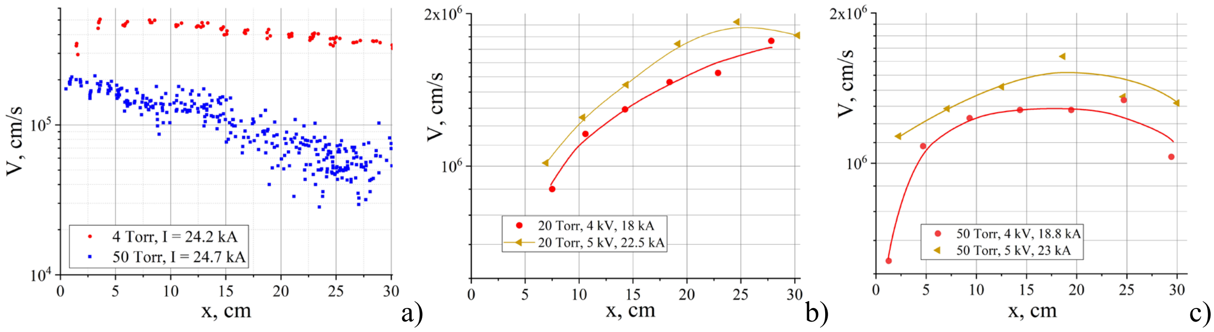

Figure 1. Plasma front velocity vs its coordinate x along the rail electrode in He and N_2 at different pressures and voltages applied to the electrodes. a) nitrogen, h=30 mm, U_0 =5 kV; b) helium, h=22 mm, P=20 Torr; c) helium, h=22 mm, P=50 Torr.

Figure 1 shows the dependences of the plasma front velocity vs its coordinate x along the rail electrode for various parameters (type of gas and its pressure, applied voltage, interelectrode gap). In general, at a fixed magnitude of the total discharge current, the velocity at the accelerator output increases both with a decrease in gas pressure and with a choice of a lighter gas. These facts are consistent with other works. However, the revealed distribution of the plasma front velocity along the electrodes is really new experimental information. The obtained velocity distributions indicate the need for a correct choice of the electrodes length in order to obtain the maximum velocity at the accelerator output. In fact, this statement applies to any working gas, not just nitrogen and helium.

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ON THE WAY TO STATIONARY PLASMA GENERATION IN A HELICON RF PLASMA SOURCE*

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The first wall problem of a fusion reactor is one of the main directions in the development of the energy of thermonuclear fusion. The study of the interaction of plasma flow with various materials (PMI studies) in linear plasma devices is low-cost alternative compared to tokamaks; however, such installations require the development of stationary plasma sources with a high particle flux. Radio-frequency sources are an alternative to the widely used arc plasma generators, their advantage is the absence of electrodes and, as a result, impurities in the plasma. To carry out PMI studies, it is necessary to create a dense plasma, an ion flow $\Gamma_i=10^{22}$-$10^{23}cm^{-2}s^{-1}$ and a power flux above 1 $MW\cdot m^{-2}$ on the surface of the material, which, in turn, requires an increase of the power. Helicon plasma sources are the most efficient among other electrodeless plasma generators, since ionization occurs throughout the plasma volume due to the propagation of helicon waves, in contrast to the absorption of excitation energy in a thin peripheral layer in inductive sources.

The classical helicon source consists of a discharge dielectric chamber with an external RF antenna in an external magnetic field. One of the most important problems of helicon facilities, which prevent reaching the stationary regime of plasma generation, is the heating of the dielectric discharge chamber by plasma. This work is devoted to the study of the processes of interaction between the plasma and the wall of the dielectric chamber, as well as methods of combating its erosion and destruction.

The helicon plasma source for PMI studies has been developed at Budker Institute of Nuclear Physics SB RAS. It is based on a helicon discharge with converging magnetic field and mirror configuration of field lines in the RF antenna region [1, 2]. The source has excitation power of up to 25 kW, an external magnetic field of 100-500 G. Pressure in the discharge is of 5-45 mTorr (H_2), transverse plasma size is of 8-10 cm and a characteristic density of 10^{12}-10^{13} cm^{-3}, an electron temperature of 5-10 eV and discharge duration 1-5 s. Chamber heating was experimentally studied. Thermocouples and an infrared thermal imager were used to measure the chamber temperature during the experiment. Local heating zones were found, coinciding with the points of the highest potential of the antenna. Experiments were carried out to increase the duration of the discharge. As the next step to stationary plasma generation regime the Faraday internal shield was developed and installed. It is based on earlier experimental and theoretical investigations demonstrated the effectiveness of Faraday shields to protect the discharge chamber from plasma exposure [3, 4, 5]. Experiments on plasma generation were carried out, the influence of shield was investigated on the radial distribution of density and electron temperature. The efficiency of power transfer into the plasma was measured using the plasma transformer model and Rogowsky coil [6]. A significant decrease in the chamber temperature was achieved when using the Faraday screen. Finally, it was developed a conceptual design of discharge chamber with double Al_2O_3 wall with cooling water shell [7]. The simulation of heating power and water coolant distribution are performed.

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METHODS FOR INCREASING THE BEAM CURRENT IN AN ELECTRON SOURCE WITH A MULTI-ARC GRID PLASMA CATHODE BASED ON AN ARC DISCHARGE WITH A HOLLOW ANODE

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The promise of using electron sources with a plasma cathode based on a low-pressure arc discharge with grid/layer stabilization of the emission plasma boundary, and a plasma anode with an open plasma boundary, has been repeatedly demonstrated for surface modification of various materials and products, leading to a multiple improvement in the functional properties of their surface, surface modifications of materials unattainable by other methods [1]. However, the use of planar beams for processing materials and products of cylindrical and more complex shapes has a number of disadvantages, the main of which is the geometric shadow effect, which does not allow uniform surface treatment. The problem described above can be solved using electron sources capable of generating a radially converging electron beam, which has already been the subject of several works [2, 3] and interesting results have been achieved.

Taking into account the experience of generating an intense submillisecond electron beam in an electron source with a multi-arc plasma cathode [4], a number of preliminary experiments were carried out on the generation of a radially converging electron beam with a multi-arc grid plasma cathode using two approaches to achieve a beam energy density that satisfies the requirements for modifying the surface of materials and products . This paper describes ways to increase the beam current in such a system both by changing the design features of the system and by using circuit solutions. The first (structural) method is to change the cell size of the emission grid, which stabilizes the boundary of the emission plasma. It is shown that the installation of an emission grid with a finer cell leads to a more uniform filling of the space of the plasma emitter with plasma due to the formation of the “hollow anode” effect, which consists in the effective ionization of the gas by primary electrons generated in the cathode spot and accelerated in the cathode potential drop. The second method (electrotechnical) is the introduction of electrical resistance into the collector circuit, which makes it possible to create a negative auto-shift of the potential relative to the “ground” on it, making it difficult for secondary electrons to escape to the collector, which are formed as a result of gas ionization by electron impact in the accelerating gap, which makes it possible to generate beam plasma in collector area. This leads to a decrease in the front of the current pulse in the accelerating gap and, as a consequence, the beam current.

The totality of the measures taken makes it possible to increase the current in the accelerating gap by more than 1.5 times and achieve a beam energy density of 20 J/cm2·pulse at the collector, which is sufficient to melt the surface of many materials and products.

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G2-O-009901

CONTROL OF THE BEAM POWER IN A SOURCE WITH A PLASMA CATHODE BY SIMULTANEOUSLY CHANGING THE EMISSION PLASMA CONCENTRATION AND THE ION LAYER WIDTH

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Electron beams are a promising instrument for both fundamental research and industrial applications. One of the promising sources of electrons is a source with a plasma cathode with layered stabilization of the boundary of the emission plasma [1].

The paper [2] demonstrates the possibility of controlling the electron beam current in the “SOLO” electron source [3] with a plasma cathode based on a low-pressure arc discharge with layer stabilization of the emission plasma boundary in two ways. The first method is based on the control of the discharge current (the concentration of the emission plasma), and the second method is based on the use of grid control (the mode of operation of the plasma triode) at a constant amplitude of the arc discharge current.

In this work, to expand the range of controllable power of the electron beam during its generation pulse, the two above-described control methods are combined.

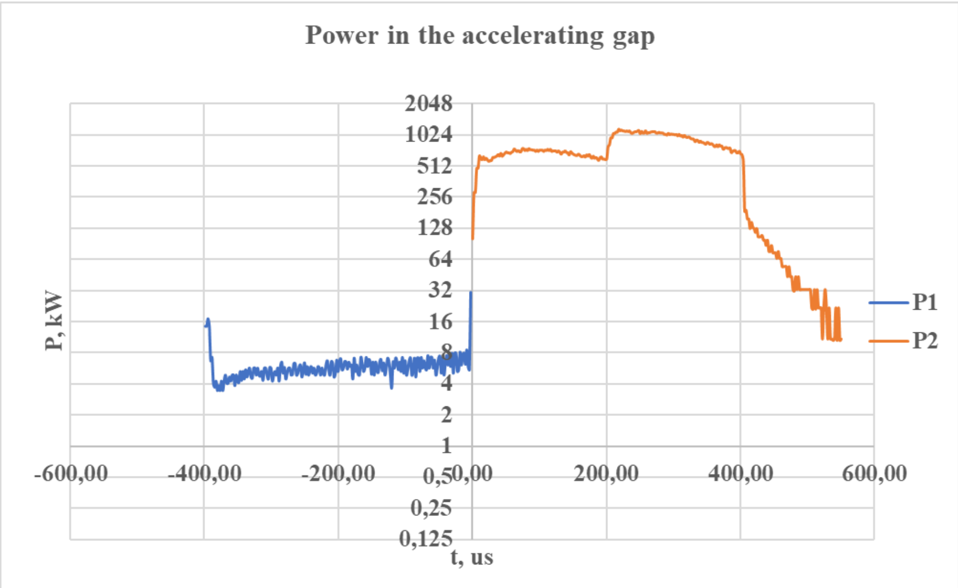

Fig.1. Beam power variation during its generation pulse under combined control.

Thus, the experiments performed indicate the possibility of expanding the range of dynamic control of the electron beam power from 6 to 1100 kW during its submillisecond pulse.

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POWERFUL HIGH-VOLTAGE PULSE GENERATOR OF NANOSECOND DUAL PULSES

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The paper presents the results of a study of the modes of operation of a pulse generator of double pulses, made of series-connected single and double forming lines. Dual pulse generators are used in accelerators of Intense Pulsed Ion Beams [1, 2]. The first pulse serves to form a dense plasma bunch of an ion source in the diode system of the accelerator. The forming lines are powered by 2 pulse transformers based on pseudo-spark (PSS) arresters. The duration of the generated voltage pulses is 60 ns, the voltage of the first pulse generated by a single forming line (SFL) is 200 kV, the second pulse generated by a double forming line (DFL) is up to 500 kV. The impedances of both lines are 9 ohms. The synchronization system based on controlled pseudo-spark gaps of the generators provides adjustment of the pause between pulses within a fairly wide range with a maximum spread within 100 ns. The generator also provides for more accurate synchronization due to the use of controlled three-electrode spark gaps OFL and DFL.

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SWITCHING CHARACTERISTICS OF THE GUIDED THREE-ELECTRODE SPARK GAP SWITCH WITH PRESSURIZED GAS

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The report presents the results of investigations of the switching characteristics of a guided three-electrode spark gap. The trigger electrode is made in the form of a thin metal diaphragm with a hole in the center. The control of the spark gap was provided by a rapid change in the potential of the trigger electrode, and breakdown occurs between the gaps under conditions of sharpening inhomogeneous electric field strength determined by the special shape of the electrodes. The switched voltage was in the range of 100–250 kV, with a maximum value of the switched current of up to 50 kA. The spark gap ensured the formation of the branching structure of the spark channel, which provided a reduction in electrode erosion and improved its switching characteristics. The influence of the composition of the gas mixture and its pressure on the switching characteristics of the spark gap was determined.

PLASMA CATHODE SWITCHES BASED ON THE CAPILLARY DISCHARGE IN SUB-MILLIMETER SLITS*

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A series of experiments on investigation of switches (eptrons [1,2]), which represent a combination of capillary discharge with plasma cathode, is presented. Such devices are able to provide a delay of the breakdown development up to hundreds of ns with a switching time ~ 1 ns in a wide range of pulse repetition frequencies (100 kHz and higher) and voltages (~ 5-200 kV) at switching currents up to units of kA.

The first part of the report presents the results of studies devoted to the influence of different design parameters of the switches separate elements (cathode node, capillary structure, external conductive shield of the capillary). In particular, the influence of the capillary channel shape and its width in the range from 0.2 to 1 mm is considered. A hollow cylindrical Ti cathode with an inner diameter of 2.6 cm and a length of 90 cm with and without additional ignition was used as a cathode assembly. A rectangular hole (60×6 mm) was made in the side surface of the cylinder into which the capillary structure was integrated. Studies were performed using helium with a pressure of 1-20 mbar as operating gas. To form high-voltage pulses on the storage capacitance a solid-state generator with pulse repetition frequency up to 200 kHz in a burst operation mode was used.

In the second part of the report the results of gas type and pressure influence on the switch operating parameters for the capillary construction with a rectangular slit of 10x0.3 mm cross-section and length of 60 mm fabricated from Al_2O_3 plates are presented. Switch cathode node consisted from two oppositely located 3 mm long accelerating gaps limited by SiC cathodes and a molybdenum grid with a geometric transparency of 90%. The accelerating gaps were separated by a 10 mm long drift space. Studies were performed with He, Ne, Ar, H2 in the frequency range of 1 - 20 kHz at 20 - 30 kV and an active load of 33 - 300 Ohm. Comparative characteristics in terms of breakdown delay time, switching time, efficiency under the specified conditions are presented. The main difference in the performance with different gases is observed in the first 5 ns, when the discharge is formed. Nevertheless, the total efficiency of energy transfer to the load does not change by more than 10% and lies in the range of 73-82%. Thus, the investigated switch is able to efficiently operate with various gases in a wide range of conditions.

Also, the results of excitation of various gas-discharge laser media by generators based on the presented switches are demonstrated. For copper, calcium and barium vapor lasers there was a many-fold increase in the average output power in comparison with the case of pumping by a traditional generator based on magnetic pulse compression with a longer excitation pulse edge (~ 30-50 ns).

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PROPAGATION DYNAMICS OF GUIDED STREAMER IN HELIUM AND ARGON ATMOSPHERIC PRESSURE PLASMA JET

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Atmospheric pressure plasma jets (APPJs) are currently a highly attractive scientific topic. APPJs in a noble gas flow have prospects for implementation in medical and biological technologies. A plasma jet generating with a dielectric barrier discharge is one of the widely used methods, while the plasma jet is formed by the passage of guided streamers along the gas flow.

In this report, guided streamer dynamics in helium and argon APPJs generated by dielectric barrier discharge with a tailoring applied voltage is described. Free jets and jets in interaction with dielectric and conducting targets were studied. The high-speed imaging with the synchronous electrical measurements has revealed some features of the streamer behavior evolution during a cycle of applied voltage for helium and argon plasma jets. The new data enlarge the results presented in [1,2] and references within.

Ionization waves in the form of a guided streamer in helium and argon jets at determined experimental parameters were obtained. The repetitive and reproducible mode of the guided streamers in the helium and argon plasma jet can be controlled by the applied voltage and gas flow. The complex dynamics of the streamer touching the target is shown. The matching of spike current pulses through the target with the streamer touching the target is observed. Using the monitoring of the current spikes is possible to organize the control of the streamer's touching the target and the dosing of the jet impact on the target object.

The study was financially supported by the Russian Science Foundation (project 22-29-01215, https://rscf.ru/en/project/22-29-01215/).

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ION-PLASMA SOURCES PARAMETERS SELECTION AND USAGE TO OBTAIN A COATING WITH THE REQUIRED STOICHIOMETRY

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Various hardening methods are used to improve the performance of HSS cutting tools. The most common way to harden a tool is to apply wear-resistant coatings [1]. This is the most effective way to ensure the optimal combination of hardness-ductility [2]. Electron Beam Physical Vapor Deposition (EB-PVD) [3,4] is the most common of the variety of coating options. One of the perspective EB-PVD coating compositions is (TiYAl)N coating.

Recent researches showed noticeable increase in wear resistance (250-270%) in comparison with an uncoated tool [5]. However, the content of each metal influence the physical properties of the coating [5]. Thus, one of the issues is to select the right technological parameters to get the required coating stoichiometry.

The article focuses on the dependence of the ion current on polar coordinates usage to calculate the parameters of an ion-plasma source. Figure 1 shows a diagram of the setup for carrying out the experiment in order to get the polar plot. The plant is equipped with two electric arc evaporators and PINK. During each experiment only one arc evaporator was active (Ti, Al or Y) so the dependence of the ion current on polar coordinates was received. This data was used to obtain a Ti-Al-Y coating of the required stoichiometry. The received coating was tested to measure the stoichiometry, adhesion and microhardness.

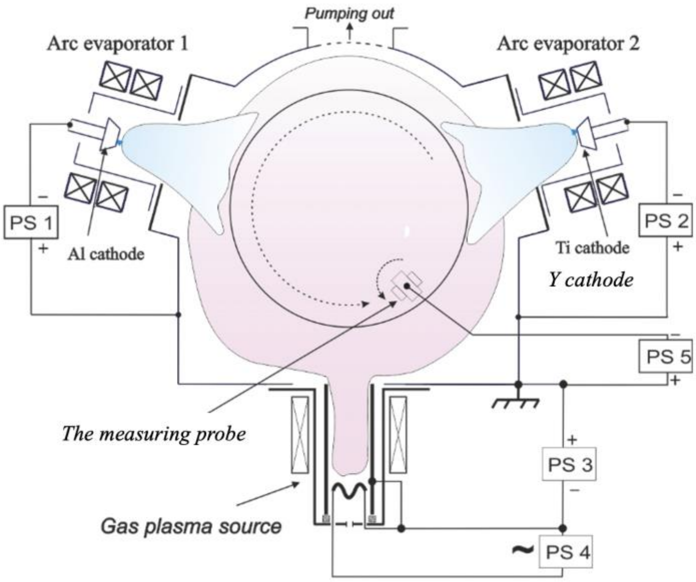

Fig.1. Experimental installation NNV-6.6 I1.

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PLASMA GENERATION IN A HIGH-CURRENT GLOW DISCHARGE WITH A HOLLOW CYLINDRICAL CATHODE USING TWO ELECTRON SOURCES *

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Experimental distributions of plasma parameters in the volume of a hollow cathode of a high-current non-self-sustained low-pressure glow discharge supported by electron injection from one and two electron sources located on the upper and lower bases of the cylindrical hollow cathode are obtained. A plasma source based on an arc discharge with an integrally cold hollow cathode is used as an electron source. The possibility of applying the superposition principle to predict the distribution of plasma concentration in the hollow cathode of a high-current low-pressure glow discharge with two electron sources is investigated. The distributions of the plasma parameters were measured at arc discharge currents of 20 and 45 A and glow discharge currents up to 200 A. With an increase in arc discharge currents by about 2 times, from 20 to 45 A, the accuracy of the superposition principle decreases. The maximum degree of inhomogeneity of the plasma concentration when two sources of electrons with currents of 20 A were turned on in the longitudinal direction was 25%. In the radial direction, it was 52%. The maximum discrepancy between the inhomogeneity coefficients for the experimental distribution and the distribution obtained as a result of summing the data obtained with separate operation of electron sources amounted to 8%. When two sources of electrons with currents of 45 A were switched on, the maximum inhomogeneity in the longitudinal direction was 8%, in the radial direction, it was 34%, and the maximum mismatch of the inhomogeneity coefficients was 25%.

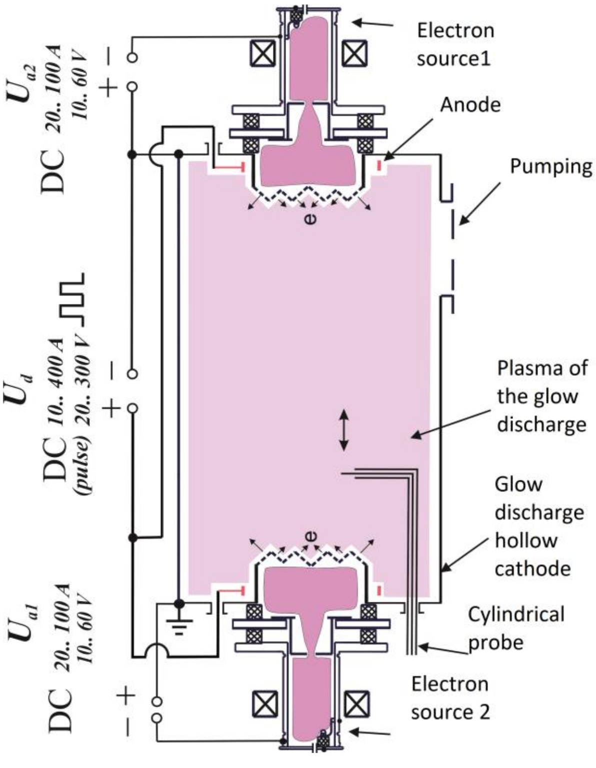

Fig.1. Experimental installation.

* The work was carried out within the framework of the state task of the Ministry of Science and Higher Education of the Russian Federation on the topic No. FWRM-2022-0001.

FEATURES OF LOW-TEMPERATURE PLASMA GENERATION IN EXTENDED HOLLOW CATHODE WITH EXTERNAL ELECTRON INJECTION *

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This paper presents the results of studying the parameters of a non-self-sustained glow discharge plasma inside the cavity of extended hollow cathodes of various shapes. Plasma generation in such cavities was carried out using a non-self-sustained glow discharge, the cathode of which was the internal cavity of an extended metal tube, and the anode was a flat electrode located near the end of the cathode. To generate a homogeneous plasma along the entire length of the hollow cathodes, electrons were additionally injected through the grid from the auxiliary discharge plasma. The operating pressure in the experiments was about 1 Pa and lower, the voltage of a non-self-sustained glow discharge was up to 300 V, at currents up to 10 A. The plasma concentration along the entire length of the hollow cathodes reached at least 10^{17} m^{-3}.

This work is a continuation of experimental studies of plasma parameters of a non-self-sustained glow discharge [1, 2]. The plasma parameters were measured with the power of cylindrical Langmuir probes installed inside the cavity of hollow cathodes.

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* The work was carried out within the framework of the state task of the Ministry of Science and Higher Education of the Russian Federation on the topic No. FWRM-2022-0001.

BRIGHTNESS CHARACTERISTICS OF A SERIAL PULSED XENON LAMP IN THE MODE OF ULTRASHORT PULSES

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To solve a number of applied problems, effective radiation sources with an isolated body of luminescence and high brightness in the visible and short-wave UV (200...300 nm) spectral regions are required. To date, among such sources, the most technologically advanced are tubular pulsed xenon lamps [1]. However, the possibilities of increasing the brightness temperatures of lamps in typical operating modes (pulse duration τ~100... 300 microseconds) by increasing the flash energy are limited by a sharp decrease in their durability and the effect of reversible opacity of quartz. The latter limits the brightness temperatures in the short-wave UV range at the level of ~10000...11000 K.

One of the ways to increase the spectral brightness of pulsed xenon lamps radiation can have a significant reduction in the characteristic time of energy release. Indeed, if the diameter of the plasma channel at the moment of maximum power is significantly smaller than the diameter of the lamp bulb, then the output of high-temperature radiation will mainly be carried out through a layer of cold gas (xenon), largely shielding the rigid component of the plasma spectrum, which causes the effects of reversible opacity of quartz.

The paper presents the results of a study of the brightness characteristics of a serial pulsed xenon lamp INP-7/80 in the modes of ultrashort (τ ~1...3 microseconds) power supply pulses.

The lamp was included in the circuit C_0 = 0.4 μF, U_0 = 30 kV with an air trigatron. The inductance of the discharge circuit is ~2.1 μH. The discharge was of an oscillatory nature with a strong attenuation, the duration of the half-life of the current is ~3 microseconds; the characteristic time of the power supply is ~1.5 microseconds. The discharge current is at a maximum of ~11 kA.

According to the measurements, the maximum brightness temperatures in the short-wavelength UV region of the spectrum are ~18,700 K and correspond to the radiation flux averaged over the entire side surface of the lamp. The radiation flux of the lamp in the short-wave UV region is two orders of magnitude higher than the corresponding flux of tubular xenon lamps in typical operating modes.

In the visible region, the maximum temperatures averaged over the surface are ~20,000 K. Measurements of local radiation fluxes with a spatial resolution of ~1 mm^2 have shown that the real brightness temperatures of the plasma (i.e., without averaging over the surface) are significantly higher (~29,300 K) and closely approach the temperatures of the so-called "saturated" brightness of xenon plasma.

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DISCHARGE AND EMISSION CHARACTERISTICS OF A COLD-CATHODE COMPACT PROTON SOURCE

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The description of the design and characteristics of the discharge system of a compact proton source based on a hollow cathode discharge initiated by a reflective Penning type gas discharge are presented. The geometry of the discharge system is a modification of the well-known design of the plasma electron source [1]. Discharge system of ion source operates in continuous and pulsed-periodic regimes. Ion extraction and beam formation are carried out by a three-electrode optical system. Its design allows it to operate at 30 kV accelerating voltage and produce proton and molecular hydrogen ion beams with current densities up to 100 mA/cm^2. In continuous regime, the total ion beam current is 10 mA at a discharge current of 450–500 mA and an extraction orifice diameter is 3.5 mm. The mass spectrum of ions was obtained using the 36 cm mass-separating magnet. The mass separated ion beam contains 1 mA protons.

This research was funded partially of state task of Institute of High Current Electronics SB RAS project FWRM-2021-0006.

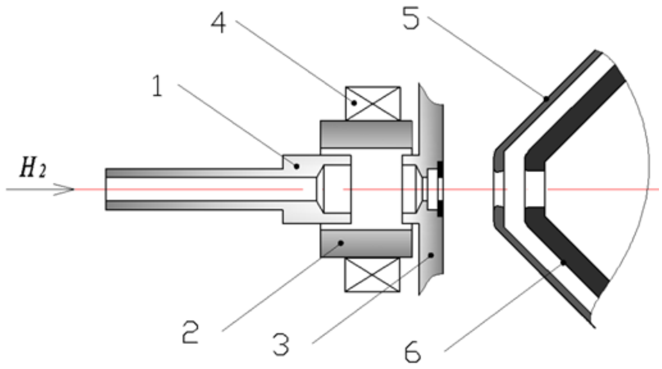

Fig. 1. Sectioned view of the proton ion source.
1 – Hollow cathode, 2 – Anode, 3 – Plasma electrode, 4 – Permanent magnet, 5 – Screening electrode, 6 – Ground (accel) electrode.

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PULSED MEGAAMPERE NEUTRON GENERATOR BASED ON PLASMA FOCUS CHAMBERS

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The paper describes a high-voltage facility based on a pulsed current generator (PCG) and a load as a plasma focus chamber (PF) through which flows a periodic discharge with a current amplitude of ~ 1 MA and a period of ~ 10 µs. The facility is used as a source of pulsed neutron radiation and provides for neutrons with an energy of 2.5 MeV an output level of $(5\div8)\cdot10^9$ neutrons/pulse., for neutrons with an energy of 14 MeV an output level of $(5\div8)\cdot10^{11}$ neutrons/pulse. and neutron pulse duration (30÷60) ns.

The PF chamber consists of two coaxial electrodes separated by an insulator and it is a sealed gas-filled device. The inter electrode space of the PF chamber is filled with deuterium or a mixture of deuterium and tritium at a pressure of tens of Torr to implement fusion reactions $D(d,n)He^3$, $D(d,p)T$, $D(t,n)He^4$ и $T(t,2n)He^4$. When energy is transferred from the PCG to the PF chamber, a discharge develops in it near the insulator surface and a plasma-current sheath is formed, which further accelerates along the electrodes, scoops up gas in the inter electrode space and contracts on the chamber axis into a pinch formation.The pinch lifetime is tens of ns, and its dimensions are several mm, which makes the PF chambers a point source of nanosecond pulsed neutron radiation.

The facility features and operation regimes with the PF chamber are considered. The main characteristics of the PCG for several configurations were determined, the inductance of the facility was 18 nH, and the maximum amplitude of the discharge current was 1250 kA at a charging voltage of 23 kV. The results of the PF chambers various configurations operation are presented. The dependences of the neutron yield and the life-time of the chambers on the total capacitance of the PCG, which varies in the range from 108 to 144 µF, are shown. On the basis of the studies, the requirements for the design of the PCG and the PF chamber were formulated, which were subsequently implemented in the ING-105 pulsed neutron generator.

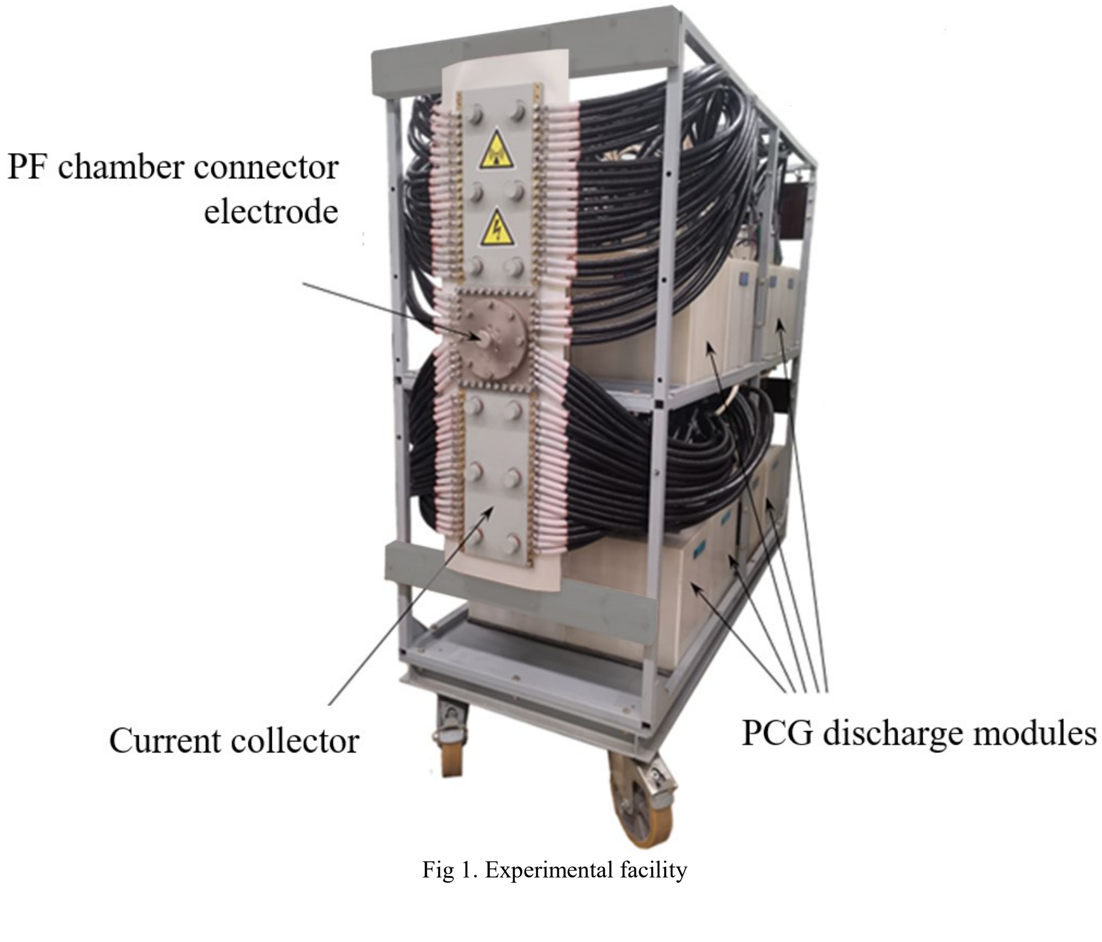

Fig 1. Experimental facility

ANALYSIS AND OPTIMIZATION OF RADIO-FREQUENCY PLASMA DRIVERS WITH VARIOUS FARADAY SHIELDS FOR LONG PULSE OPERATION

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Many modern nuclear fusion facilities require neutral beam injectors capable of operating with long, multi-second pulses [1]. An example is the high-energy injector prototype currently being developed in Budker Institute of Nuclear Physics for plasma heating in the TRT tokamak [2]. The neutral beam is produced by neutralizing a beam of negative hydrogen ions, which is generated by a 9A ion source with four radio-frequency (RF) plasma drivers.

A scheme of the plasma driver is shown in Figure 1. Plasma generation is initiated with a short arc discharge in the ignition unit and sustained with the RF field produced by the driver antenna when hydrogen is supplied to the driver [3].

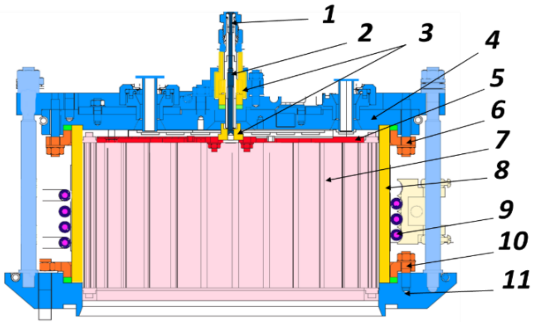

Fig. 1 Scheme of the RF plasma driver: 1 - hydrogen dispenser, 2 - hydrogen inlet channel, 3 - ignition unit, 4 - upper flange, 5 - rear flange screen, 6 – upper clamping flange, 7 – Faraday shield (plasma volume inside), 8 - Al_2O_3 ceramics, 9 - three-turn antenna, 10 – bottom clamping flange, 11 - bottom connecting flange.

One of the main problems of injectors that limits the pulse duration is high thermal loads on the plasma driver. Several water-cooled Faraday shields have been developed to protect the driver ceramic inside wall from plasma. The main disadvantage of using these shields is that they significantly reduce the efficiency of RF power transfer to the plasma. [4]. The main purpose of this work was to compare the performance of RF drivers with different shields and optimize the parameters of the drivers. To study the drivers, thermal loads were simulated for each screen and compared with the experiments. The experiments were carried out with plasma generation on a test bench equipped with devices for measuring density of the ion current extracted from the driver plasma, measuring the driver elements temperature and measuring temperature and flow of the cooling water. Using the data from the model and the experiments power dissipation within the driver and power transfer efficiency were estimated.

As the result of the study an optimal shield configuration for continuous operation was achieved with 57% power transfer efficiency at 32 kW of driver input power. The shield reaches thermal equilibrium after 15 seconds of operation.

The work was carried out with the support of the Ministry of Science and Higher Education of the Russian Federation.

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METHODS TO CONTROL THE GENERATION OF ACTIVE RADICALS BY COLD PLASMA JET FOR BIOMEDICAL APPLICATIONS*

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Cold plasma jet (CPJ) is an actively used and investigated tool for treating biological objects of different origins. CPJ is a type of gas discharge in which the streamers generated by applying a voltage propagate along the gas flow outside the discharge volume to the target. Insignificant heating of biological object surface caused by interaction with CPJ enables predominantly influence by active particles induced during propagation and interaction of gas-discharge plasma with aqueous or gaseous medium surrounding the object. Nitrogen and oxygen-containing active radicals produced in this way actively interact with cells of biological tissues, affecting the processes of vitality, including the shown selective effect on healthy and cancer cells [e.g., 1, 2]. It is assumed that OH, H_2O_2 и O_2 are the main active particles that set the increased level of active oxygen species in CPJ-treated cells [3]. The aim of this work was to investigate methods to intensify the generation of active radicals during CPJ propagation. Electrical and spectral parameters of CPJ in the area of interaction with a biological object were investigated and methods to control the generation of active radicals were determined:

1. The frequency of current touching the object of influence f_I can be equal to the frequency of applied sinusoidal voltage f_U ($f_I = f_U$) or multiple of 2 ($f_I = f_U/2$) or 4 ($f_I = f_U/4$) [4]. With the increase of applied sinusoidal voltage frequency in modes with equal current frequency in the interaction area with the object ($f_I = f_{U1} = f_{U2}/2 = f_{U3}/4$) the current amplitude increases that leads to the increase of pulse power injected into gas discharge and accelerates ionization processes, in particular, intensification of hydroxyl radical OH generation (from H_2O molecules with the following occurrence of H_2O_2 peroxide synthesis reaction).

2. When initiating CPJ by pulsed voltage with adjustable pulse duration it was found that in the operating voltage range with decreasing voltage pulse duration the current amplitude increases, and streamers forming CPJ become more intense with a regular character of propagation, respectively, the generation of active radicals, including OH hydroxide, in the interaction area of CPJ with the object increases.

3. Increasing humidity in the area of CPJ impact on a biological object changes the plasma characteristics and increases the rate of generation of hydroxyl radicals. Accordingly, the additional introduction of water vapor into the area of interaction of CPJ with the object intensifies the generation of hydroxyl OH.

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Z-PINCH FORMATION BY A PLASMA FLOW OF A HIGH-CURRENT VACUUM DISCHARGE*

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The possibility of increasing the implosion current of a metal-plasma liner [1] by changing the mode of propagation of the arc source plasma in the interelectrode gap when replacing the grid on the cathode with a solid electrode was tested. On Fig. 1, on the left, is a diagram of the arc source used in the experiment. The cathode (4) of the generator was formed either by a stainless steel mesh with a transparency of 70% or a solid stainless steel electrode. At a voltage of 25 kV at the arc power source, the current amplitude was I_{arc} ~ 140 kA, with a rise time of ~ 5.3 μs. A frame of visible radiation of the plasma jet at the sixth microsecond after the onset of the arc current during plasma injection onto the grid is given nearby. When the grid at the cathode was replaced by a solid electrode and a delay time of 8 μs between the onset of the arc current and the current of the GIT-12 generator, the implosion current amplitude increased from 2.2 MA to 3.1 MA, and the energy supplied to the liner reached ~100 kJ/cm. Figure 1 shows a diagram of the setup for carrying out the experiment. The plant is equipped with two electric arc evaporators and a hollow cathode plasma source for ion nitriding of the coating process.

On Fig. 1, on the right, shows frames in the visible range of the spectrum, recorded using an HSFC Pro optical camera with an exposure time of 3 ns and an interval between frames of 60 ns. Under the same operating conditions of the GIT-12 generator, the formation of the outer plasma shell and the vacuum arc, implosion is stable in the case of a grid cathode (Fig. 1a). The current sheet corresponds to the outer boundary of the glow of the plasma sheath [1]. For a solid cathode, the implosion process is unstable (Figs. 1b, 1c), and in the absence of an outer plasma shell, instabilities begin to develop already at the initial stage of implosion (Fig. 1b).

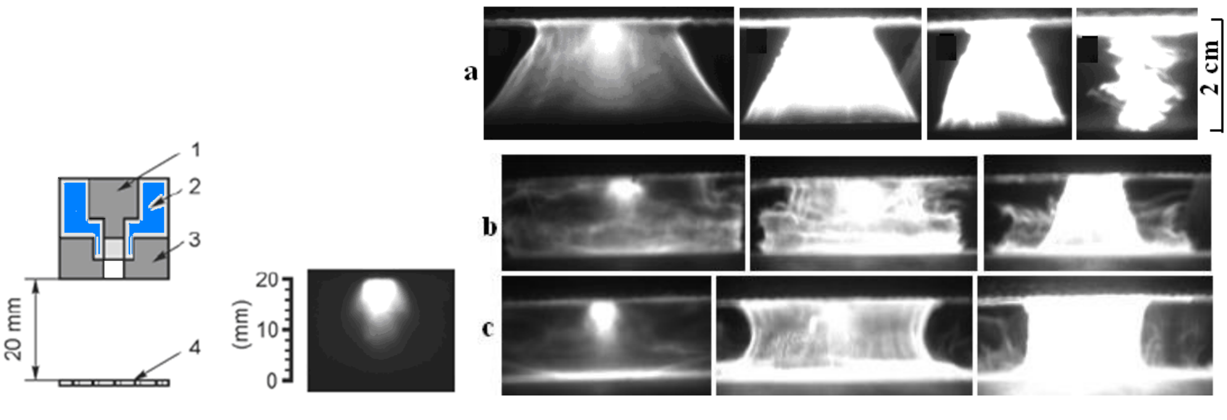

Fig.1. On the left, the electrode circuit of the arc source: 1 - aluminum cathode of the vacuum arc plasma gun, 2 - polyethylene insulator, 3 - aluminum anode of the vacuum arc plasma gun, 4 - generator cathode. On the right, the influence of the initial conditions for the formation of a Z-pinch load on the implosion process at constant parameters of the GIT-12 generator and the vacuum-arc discharge power source that forms the metal-plasma liner: a) - grid cathode with a transparency of 70%, b, c - solid cathode , b – there is no outer plasma shell.

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INFLUENCE OF POLARITY AND RATE OF CURRENT GROWTH OF A VACUUM HIGH-CURRENT DISCHARGE ON THE CHARACTERISTICS OF PLASMA JETS*

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Plasma sources based on high-current vacuum discharges in vapors of aluminum and copper electrode materials initiated by breakdown over a ceramic surface are studied. Capacitive power supplies made it possible to implement 4 modes of oscillatory current discharge with amplitudes of 4–18 kA and rise times of 320, 450, 630, and 1300 ns. To measure the characteristics of the plasma flow, double probes with a reference electrode were used. The probes had a coaxial design, the outer electrode made of a copper tube was the reference electrode, relative to it the voltage U_{sm} = – (30–50) V was applied to the inner electrode. The probes were installed at a distance of 60 and 110 mm from the end face of the plasma source. The technique for measuring the characteristics of a plasma flow is described in detail in [1].

The results of the study are shown in Fig. 1. For the geometry of the discharge gap (see Fig. 1b) with a corundum ceramic insert for both materials, the influence of the polarity of the central electrode on the characteristics of the plasma flow was tested. With a negative polarity of the central electrode, the plasma velocity is, as a rule, 10-15% lower than with a positive polarity. The studied discharge regimes made it possible to establish that the plasma flow has a maximum velocity in the initial stage of arc formation in the front section up to half the amplitude of the high-current discharge current. Fig. 1b demonstrates the significant influence of the current rise rate on the plasma jet formation. Due to the negligible ablation of the ceramic, the plasma flow mainly consists of ions of the electrode material. Plasma flows of copper and aluminum ions with velocities from 5 cm/μs to 12 cm/μs and concentrations up to 10^{15} cm^{-3} have been obtained.

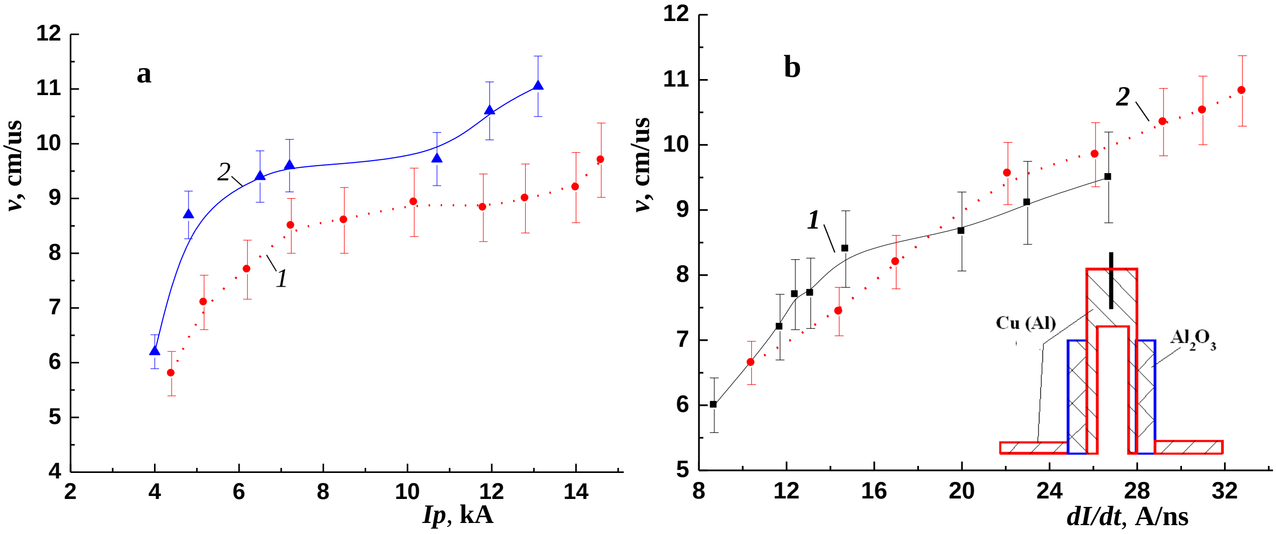

Fig.1. a - dependence of the plasma flow velocity on the amplitude of the discharge current with a half-cycle of 1250 ns for copper electrodes, 1 - central electrode - cathode, 2 - anode; b – dependence of the plasma flow velocity at the negative polarity of the central electrode of the vacuum-arc plasma gun on the average current rise rate (*dI/dt*:): 1 – Al, 2 – Cu.

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* The work was carried out within the framework of the state task of the Ministry of Science and Higher Education of the Russian Federation on the topic № FWRM-2021-0001.

LONG-PULSE PLASMA SOURCE FOR FLOW FORMING IN SMOLA MAGNETIC MIRROR DEVICE

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The key problem of plasma confinement in open magnetic traps is the suppression of particle and energy losses from the mirrors. To solve this problem, the concept of helical plasma confinement was proposed [1]. The main idea of this concept is the creating magnetic plugs moving in the reference system of plasma, whose motion relative to the plasma is created by the rotating plasma in crossed electric and helical 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 plasma flow in SMOLA device is created by a magnetically insulated discharge in axisymmetric plasma gun 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 $n \sim 10^{12} \div 10^{13}$ cm^{-3} and T ~ 5÷30 eV at a distance of 0.4 m from the gun anode. Discharge's time is controlled by power supply, gas system and varies in 0.1 ÷ 2 seconds.

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 consists of electrical probes' system (density, electron's temperature, electrical potentials), optical spectroscopes with high spatial resolution (rotation velocity, ion's temperature and electrical fields) and instruments for electrical parameters of discharge, vacuum (gas balance), as well as power systems control for all high-power circuits measurement.

The present report is devoted to the analyze of the plasma source effectiveness in the SMOLA device. This report includes the dependences of plasma parameters on the gun characteristics and experimental conditions.

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G2-P-007904

FEATURES OF TITANIUM ION BEAMS FORMATION TAKING INTO ACCOUNT ION-ELECTRON EMISSION TO REALIZE THE SYNERGY OF HIGH-INTENSITY ION IMPLANTATION AND PULSED ENERGY IMPACT ON THE SURFACE*

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This paper shows the possibility of submillisecond duration titanium ion beams formation in the average ion energy range from 16 to 56 keV with a maximum ion current density of 1.6 A/cm^2 at a pulsed power density approaching to 60 kW/cm^2 in averaged pulses and a maximum ion current density of 3.4 A/cm^2 at a pulsed power density of 122 kW/cm^2 in individual pulses.

The dependence of the ion-electron emission coefficient on the accelerating voltage and arc discharge current is presented. It has been established that the ion-electron emission coefficient in the case of irradiation of a stainless steel target with a titanium ions beam reaches a value of two at an accelerating voltage of 30 kV.

The dependences of the radial distribution of the ion current density on the amplitude of the accelerating voltage are obtained for different positions of the collector relative to the geometric focus of the ballistic system for focusing the ion beam. It has been experimentally shown that with an increase in the accelerating voltage from 8 kV to 17 kV, an increase in the density of the measured current by a factor of 1.5 is observed, while in the range from 17 kV to 27 kV, the current density decreases by approximately 10%. Using nineteen collector probes, it was shown that due to the effect of the partially uncompensated space charge of the ion beam, the best conditions for its focusing are achieved at a distance of 20 mm behind the geometric focus of the system.

* The work was supported by the Russian Science Foundation (grant No. 22-19-00051)

INVESTIGATION OF THE ION EMISSION FROM THE PLASMA FORMED IN FERROELECTRIC SOURCE[i]

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One of the sources of particle beams are active plasma cathodes based on ferroelectric materials ($BaTiO_3$, PZT, PLZT) [1, 2]. The discharge over the surface of ferroelectric [3] occurs under the application of pulses of the driving voltage and has a number of features. Firstly, this is the low voltage value of the discharge initiation (a few kilovolts) [4]. Secondly, the discharge is characterized by the multichannel structure and moves in an incomplete stage [1].

Ferroelectric cathode can be used also as a source of the ion beams [5]. Since, due to the multichannel structure of the incomplete discharge, it is possible to form a homogeneous plasma layer on the cathode surface of a large area. This is an important requirement for the plasma source of pulse power ion diodes [6], since the emission area of the electrode is, as a rule, more than 100 cm^2.

Plasma formation on the ferroelectric surface is accompanied by a flow of neutral molecules and atoms, the source of which is the ceramic material and the layer of adsorbed gas on the ceramic surface [7]. The plasma density depends on the parameters of the control pulse (voltage amplitude and pulse duration) and on the composition of the ferroelectric material, and also on the processes of ionization of the adsorbed gas on its surface. In this regard, the purpose of this work is study of the ion current emission and the plasma parameters, depending on the discharge conditions.

Figure 1 shows the structure of a plasma source based on the $BaTiO_3$ ceramic. In the course of work the spectral studies of plasma and the ions emission were carried out in the range of pressure of the residual gas $10^{-3} \div 10^{-5}$ Torr.

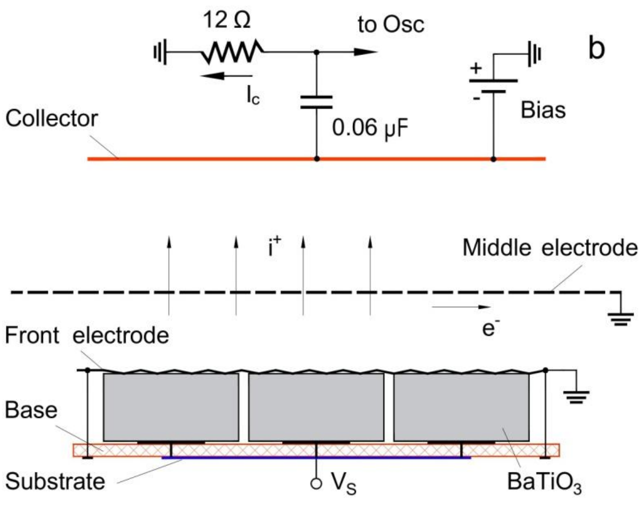

Fig.1. Experimental setup

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INFLUENCE OF COMBUSTION CONDITIONS OF A DIFFUSE DISCHARGE ON THE GENERATION OF A DISCHARGE KRCL LASER*

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The paper presents the results of experimental and numerical studies of an discharge KrCl laser. The developed 1D model includes a system of equations for the electric excitation circuit, a system of rate equations for the concentrations of plasma components, a stationary Boltzmann equation for the electron energy distribution function, and wave equations describing the development of a photon avalanche in a plane-parallel resonator.

Based on the use of this model in the discharge KrCl laser developed at the HCEI SB RAS, the pump power density was optimized for various compositions of the working mixture. The burning conditions of a diffuse discharge are shown, which provide the theoretical limit of the generation energy for a given mixture. The difference between the theoretical and experimentally measured generation energies was no more than 1%.

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OPTIMIZATION OF TARGET PLASMA PARAMETERS AT THE CAT INSTALLATION

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A new CAT (Compact Axisymmetric Toroid) installation is an axially symmetric mirror with a powerful atomic injection. The purpose of the planned experiment is to create and study the confinement of a hot ions population with an extremely high $\beta \sim 1$. The possibility of switching to a field-reversed configuration (FRC) is also considered. It is assumed that two 2 MW, 15 keV hydrogen neutral beams will be injected into the target plasma. According to the results of earlier calculations [1], for the hot ions effective accumulation formed as a result of the neutral beams capture, it is necessary that the target plasma electron temperature is in the range of several tens eV, and the linear density is sufficient for the effective neutral beams capture. To generate a target plasma with the required parameters, a technique developed earlier for plasma injection into an ambipolar trap is used [2]. The essence of the technique is to use an arc-type plasma source, which has a discharge channel with an annular configuration and operates in a magnetic field. The plasma differential rotation resulting from the $E \times B$ drift leads to the Kelvin-Helmholtz instability development, which in turn causes plasma jet ions heating. Due to Coulomb collisions, ions transfer energy to plasma electrons. A thermal barrier is formed using a special magnetic coil to suppress the electronic thermal conductivity between the central cell and the plasma source.

The purpose of this research is to obtain the target plasma using this technique and optimize its parameters. Detailed studies of the target plasma parameters have been carried out. The results of the search for the optimal ratio between plasma linear density and its electron temperature for the capture and hot ions confinement have been described.

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SYNTHESIS OF TUNGSTEN CARBIDE USING A THREE-PHASE ARC REACTOR

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Tungsten carbide is characterized by promising physical and chemical properties such as high melting point, high hardness, corrosion and acid and alkalis resistance [1]. There are a lot of methods of tungsten carbide synthesis, including arc discharge plasma method. Nowadays there is perspective open-air modification of this method [2].

The main disadvantage of synthesis of materials by plasma methods is the relatively small mass of the resulting material, which requires a large number of experiments for research work on the analysis of product properties and creating products from it. Thus, this work is devoted to the development and design of three-phase electric arc reactor, the structure and principles of which are based on the previously developed single-phase arc reactor [2].

The configuration of the discharge circuit has not changed much in the design of the reactor. Similar to the single-phase arc reactor, the discharge circuit of the reactor includes the power supply, the conductive parts of the system and the graphite electrodes. Three single-phase welding inverters are installed in the telecommunication cabinet, the inverters are powered from three-phase industrial network of 380 V, starting of the power sources is realized through the control panel, located on the front part of the telecommunication cabinet. Negative leads of power supply sources, by means of copper wires, are led out of the cabinet and connected to the aluminum plate with indentations for installation of graphite crucibles (cathode). The positive outputs of the power supplies are connected to three independent conductor sleeves for inserting graphite rods (anode). The aluminum plate and the current-carrying sleeves are installed on a hand-held drill stand.

A series of experiments on the synthesis of tungsten carbide were performed to test the operation of the three-phase arc reactor. The prepared mixture of tungsten and carbon powders (mixture weight 10 g) is placed in a graphite crucible and covered with graphite felt. After the power sources are started up, the graphite rods move into the cavity of the graphite crucible until the graphite felt contacts it, resulting in the formation of an arc discharge. The initial mixture was exposed to the arc discharge for 90 seconds and the current set on a 220 A power source. The obtained powder was analyzed on an X-ray diffractometer (Shimadzu XRD 7000 s, λ = 1.54060 Å). WC and W_2C tungsten carbide peaks were identified from the obtained X-ray diffractogram (fig. 1). Based on the results, the mass of the obtained product was increased from 1 to 10 g.

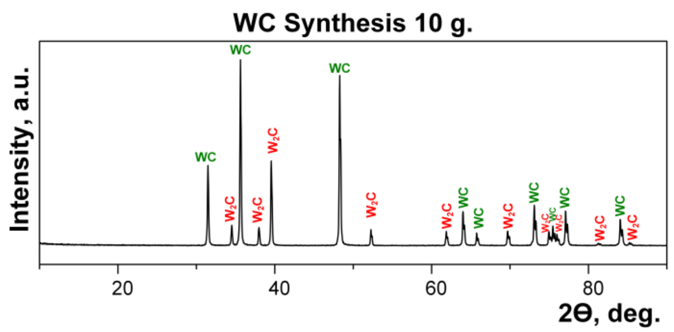

Fig.1. XRD pattern of the synthesized tungsten carbide.

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G2-P-013501

3D MODEL OF PLASMA PROCESSES IN RADIO FREQUENCY INDUCTIVELY COUPLED PLASMA TORCH 30 KW, 5.28 MHZ FOR POWDER TREATMENT

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Currently, radio frequency (RF) inductively coupled plasma (ICP) torches are used for such technologies as: spectral analysis, purification and spheroidization of fine powders, surface treatment, nanopowders production, plasma-chemical technologies [1]. The main area of research in Peter the Great St.Petersburg Polytechnic University (SPbPU) is the purification and spheroidization of fine powders. Figure 1 shows RF ICP torch with a power of 30 kW and a frequency of 5.28 MHz in the laboratory of plasma technologies of SPbPU and an example of a plasma technology for fine powder treatment.

Mathematical modeling is widely used to understand the processes that take place in RF plasma torches and to develop new plasma technologies. Previously developed 2D models are described in detail in [2–4].

This paper presents a 3D stationary model of plasma processes in the RF ICP torch of 30 kW, 5.28 MHz and shows the results of calculations for various flow rates of the plasma-forming gas (air). Figure 2 shows the plasma temperature distributions for the case of a plasma gas flow rate of 40 l/min.

The use of a three-dimensional model made it possible to observe the features of the plasma temperature distributions that could not be seen within the framework of a two-dimensional axisymmetric model. It can be seen that the plasma is tilted in relation to the axis of the plasma torch. This effect is observed in a cross-section perpendicular to the direction of the inductor ends (see Fig. 2, b). This phenomenon can be explained by the spiral shape of the inductor, in which the axisymmetric shape of the electromagnetic field is disturbed.

Fig.1. Photos of the investigated ICP torch and plasma process

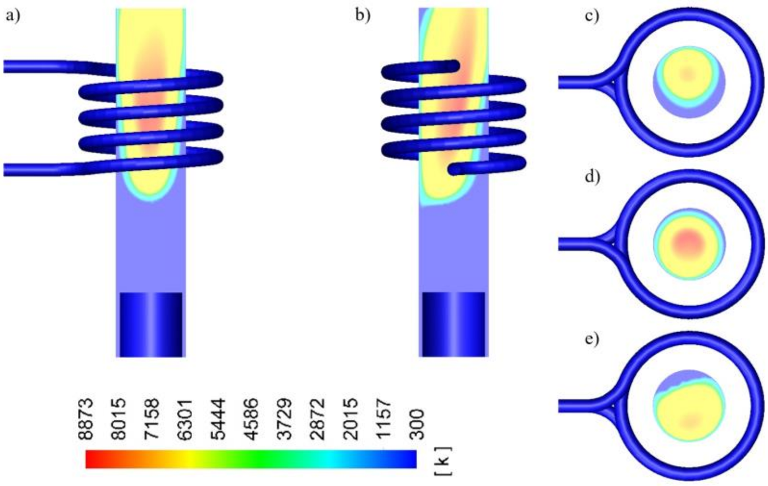

Fig.2. Results of calculation at the gas flow rate G = 40 slpm: a, b – temperature distribution in two mutually perpendicular cross-sections; c-e – temperature distributions in cross-sections perpendicular to the plasma torch axis (c – z = 150 mm, d – z = 200 mm, e – z = 270 mm)

The work was carried out within the framework of the research topic under the state assignment of Ministry of Science and Higher Education of the Russian Federation FSEG-2023-0012.

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MICRODROPLET FRACTION FILTRATION SYSTEMS FOR VACUUM-ARC DEPOSITION OF COATINGS BASED ON HEA

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The results of the development and research of systems for magnetic filtration of the microdroplet fraction by turning the arc discharge plasma flow are presented.

In vacuum-arc deposition of films based on high-entropy alloys (HEA), five or more different metals are used as a sputtered material. At the same time, the cathodes of arc evaporators, which are the source of metallic plasma, can be made of both pure metals and alloys, as well as powder compositions.

When cathodes are sputtered from metals with a low melting point, as well as from pressed and sintered powders of several metals using a vacuum arc discharge, a sufficiently large amount of a microdroplet fraction is contained in the vacuum arc plasma. The presence of microdroplets in the deposited film can make it difficult to obtain the required properties of the formed coating.

One of the most effective methods for separating the microdroplet fraction is the transport of a plasma flow through a curved pipeline in a longitudinal magnetic field. In this case, the plasma flow turns in accordance with the lines of the magnetic field, and the microdroplet fraction moves in a straight line and is deposited on the pipeline walls. The efficiency of such a system depends on the configuration of the magnetic and electric fields, as well as the geometry of the pipeline.

We have developed systems for magnetic filtration of the microdroplet fraction with a 90-degree rotation of the plasma flow, as well as a two-cathode system with a 60-degree rotation.

The paper presents the results of a study of the deposition rate, the coefficient of removal of the microdroplet fraction, the efficiency of the developed systems, as well as examples of the obtained coatings based on HEA.

This work was carried out with the financial support of the Russian Federation represented by the Ministry of Science and Higher Education (project No 075-15-2021-1348) within the framework of event No.3.1.4, 3.1.5, 3.1.12 и 3.1.13

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PLASMA DENSITY DISTRIBUTION IN A HOLLOW CATHODE OF A HIGH-CURRENT LOW-PRESSURE NON-SELF-SUSTAINED GLOW DISCHARGE WITH TWO ELECTRON SOURCES*

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The uniformity of ion-plasma treatment of the surface of large-sized extended metal and alloy products is an important issue, which can be solved by using gas plasma generated in a hollow cathode of a non-self-sustained low-pressure glow discharge supported by electron injection from several electron sources. It was shown in [1] that when two electron sources are used in an axisymmetric cylindrical plasma generation system based on a high-current non-self-sustaining low-pressure glow discharge with a hollow cathode, the principle of superposition of the plasma concentration distribution is realized.

This paper presents the results of a numerical and experimental study of the principle of superposition of the plasma density distribution in the hollow cathode of a low-pressure high-current glow discharge with two electron sources. A numerical 2D model of a non-self-sustained DC glow discharge in low-pressure mode was built using the COMSOL/DC Discharge interface. The electron density and average energy of electrons are calculated by solving the drift diffusion equations for the electron density and average energy with non-zero right-hand sides describing the birth and death of particles, the Poisson equation for the electrostatic potential is solved. The discharge is maintained by the emission of secondary electrons at the cathode and by the electron injection current of the source(s). On fig. Figure 1 shows the computational domain and plasma concentration distributions for electron injection from one and two sources. Numerical calculations have shown that when two sources are used, the principle of superposition of the plasma density distribution is realized, which is affected by the symmetry of the location of the sources, the geometry of the injection surface, and the electron current.

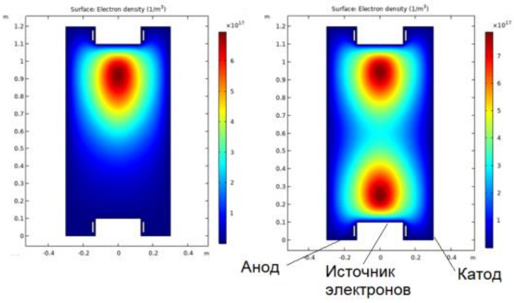

Fig. 1. Configuration of the computational domain of the hollow cathode and distribution of the plasma concentration during the operation of one and two electron sources.

It has been experimentally shown that the deviation of the experimental characteristics and those obtained as a result of arithmetic addition is no more than 15% for the pulsed combustion mode and no more than 10% for the constant mode.

The results of the numerical model are consistent with the experiment, which makes it possible to predict the distribution of plasma in the volume of the working chamber when designing large-sized systems.

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EFFECT OF LOW-TEMPERATURE PLASMA NON-SELF-SUSTAINED DISCHARGE ON PHYSICOCHEMICAL PROPERTIES OF POLYTETRAFLUOROETHYLENE SURFACE

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The effect of nitrogen flow non-self-sustained discharge plasma treatment on surface physicochemical properties of biocompatible materials based on polytetrafluoroethylene (PTFE) was investigated. The commercially available prosthesis for the cardiovascular system based on foamed PTFE (GORE-TEM®) were used as objects of the study. The plasma treatment conditions were following: the plasma-forming gas – nitrogen; the amplitude of discharge current – 5-10 A; the working pressure – 0.3 Pa; the exposure time – 5-30 minutes. The low-temperature plasma treatment was used for alteration of the structure and physicochemical properties of the PTFE-based materials, such as chemical compound, wettability, biocompatibility, etc. [1].

According to the C1s spectra obtained by XPS, the chemical composition of the PTFE-based materials was found to be altered after the low-temperature plasma irradiation in nitrogen flows. The nitrogen plasma treatment leads to 2.1 times increase of the carbon bonds in the coordination -C-C/-C-H($E_{(C1s)}$ = 285,6 eV) and 4.1 times decrease of the carbon bonds in the coordination -CF_2($E_{(C1s)}$ = 292,5 eV). The maximum content of -C-C/-C-H equal to 33.43 at.% and the minimum content of -CF_2 equal to 20.36 at.% is observed when the PTFE surface is treated with the nitrogen plasma for 10 minutes. Moreover, new chemical bonds such as CF_3, CF/O=C-O, -C–O, C-N are formed in the surface layer [2]. This phenomenon may be associated with the simultaneous processes of destruction and cross-linking in PTFE macromolecules. The CF_3 and CF bond formation is related to polymer chain breaking mechanisms and defluorination of the PTFE surface layer. The carbon atom content in the coordination C-N during a 20-minute plasma treatment is 3.35 at.%, while after a 30-minute exposure this amounts to 3.85 at.%. The chemical compound alteration of the PTFE surface layer after the plasma modification indicates that the individual impact of the bombarding particles leads mainly to a sputtering effect, leading to defluorination of the surface and the formation of a carbonaceous layer, and not to the grafting of amino / amide functional groups [3].

Polytetrafluoroethylene is known for its high hydrophobicity, which can be altered by plasma technology. The initial PTFE contact angles are 129.7° with water and 120.9° with glycerol. It was found that the contact angles both with water and glycerol decreased, that indicates the wettability improvement after plasma treatment. The minimum water contact angle (θ = 98°) and the minimum glycerol contact angle (θ =95°) is found for the 30-minute N_2 plasma-modified PTFE sample. Surface wettability improvement is due to the formation of hydrophilic functional groups (O=C-O, -C–O, C-N) in the plasma-modified material. The PTFE wettability data reveal a tendency to the free surface energy enhancement accompanied by a simultaneous increase in the surface polar and dispersive parts after nitrogen plasma treatment. The maximum surface energy value of 34.87 mN/m corresponds to the PTFE, treated with nitrogen plasma for 30 minutes.

To sum up, nitrogen flow non-self-sustained discharge plasma treatment is an effective technique for surface physicochemical property modification of biocompatible materials based on PTFE.

This work was supported by the Tomsk State University Development Program (Priority-2030).

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G3-O-000503

SOME REGULARITIES OF PLASMA-SOLUTION SYNTHESIS OF BINARY OXIDE COMPOUNDS

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It is well known to obtain metal and oxide particles from solutions under the action of a gas discharge [1, 2], while there are still very few works devoted to studying the production of binary oxide compounds from solutions under the action of low-temperature nonequilibrium plasma. Transition metal oxides are widely used in various fields of science and technology [3]. However, individual metal oxides generally have poor conductive properties and unfavorable stability, which limits their use. At the same time, binary oxide systems are free from this disadvantage. This paper presents some experimental data on the synthesis of binary oxide compounds from a mixture of aqueous solutions of nitrates under the action of a nonequilibrium gas-discharge plasma.

The technique of experiment and synthesis is described in detail in [4]. In this paper, we consider the preparation of some double oxides of transition metals, namely $(ZnO)_{0,92}$ $(CdO)_{0,08}$, NiOCuO, $NiOCo_2O$, $CoFe_2O_4$, $NiFe_2O_4$, $ZnFe_2O_4$. The synthesis of bimetallic oxide compounds occurred in two stages. First, plasma-solution synthesis of ultrafine particles from solutions of a mixture of nitrates under the action of a DC glow discharge. The second was the high-temperature treatment of the resulting hydroxonitrates and hydroxides. The temperature was selected individually based on the data of thermogravimetric analysis and varied from 300 to 1000 °C, depending on the metal cations used for the synthesis.

Studying in detail the processes of formation of a solid phase in solution using the turbidimetric method of analysis, as well as comparing the results with the data of X-ray diffraction analysis and energy-dispersive X-ray spectroscopy, we found that the process of formation of a solid phase is chemically complex and multi-stage. The kinetics of the formation of the solid phase in the solution had an induction period associated with the accumulation of active particles in the solution under the action of the plasma, and the change in the intensity of the light transmitted through the solution during the plasma treatment has an exponential decreasing character. The characteristic times of solid phase formation obtained from these dependences, as well as the induction period, decrease with increasing discharge current. As a result of hydrolysis-like processes, hydroxides and hydroxonitrates of the corresponding metals were formed in the solution. This was confirmed by the XRD and EDS data. According to the data of a scanning electron microscope and dynamic light scattering, the particles obtained were characterized by two sizes: one was about 100 nm and the other was about 1.5 μm. At the same time, on images from a transmission electron microscope, it was seen that individual particles were combined into larger ones.

The possibility of synthesizing binary oxide compounds from a solution of a mixture of nitrates under the action of a nonequilibrium gas-discharge plasma was shown. The resulting particles can then be used as catalysts, sensors, and in biomedical applications.

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SYNTHESIS OF COBALT FERRITES FROM NITRATES UNDER THE ACTION OF NON-EQUILIBRIUM ATMOSPHERIC PRESSURE PLASMA

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Spinel type ferrites have attracted great attention of the research world due to their interesting magnetic and electrical properties, such as high saturation magnetization, high squareness factor, large magnetocrystalline anisotropy, low coercive force, high electrical resistance, magnetic permeability, low eddy current loss, high Curie temperature and mechanical hardness to name a few [1]. There are a large number of methods for obtaining ferrites with a spinel type structure, such as the sol-gel method [2], hydrothermal [3], mechanochemical –synthesis [4]. One of the new and promising methods of obtaining is those based on the use of low-temperature gas-discharge plasma.

The scheme of the gas-discharge cell is shown in Fig. 1. A DC glow discharge was ignited between a titanium anode and an aluminum plate as a cathode. This configuration allows to increase heat dissipation and reduce overheating and, as a result, wear of the electrodes. Mixtures of iron, cobalt nitrates were used as objects of study.

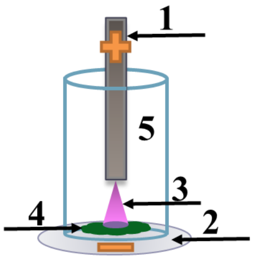

Fig.1. Scheme of the experimental setup. 1 – titanium anode, 2 – aluminum cathode, 3 – plasma region, 4 – initial salt of metal nitrates (crystal hydrates), 5 – quartz tube.

The composition and morphology of the resulting powders were studied by X-ray phase analysis (XRD: DRON 3 M, Burevestnik, Russia), scanning electron microscopy (SEM: Tescan Vega 3SBH, Czech Republic) and energy dispersive analysis (EDS: Aztec EDS, Oxford Instruments Ltd., England), and dynamic light scattering (DLS: Photocor Compact –Z, Russia).

EDS and XRD data showed that the synthesized powders have a chemically complex composition and were iron and cobalt oxides of complex stoichiometry. According to dynamic light scattering data, the obtained powders consist of two characteristic fractions. The main fraction (94%) was represented by particles 105 ± 4 nm in size. And the other fraction (6%) consists of particles 18 ± 4 nm. The value of the Zeta potential was 20.5 mV, which indicates a high aggregative stability of the colloidal solution of the resulting nanoparticles. X-ray phase analysis showed that the product contains particles of cobalt ferrite CoFeO4, with a spinel crystal structure. The images obtained on a scanning electron microscope clearly showed a well-developed surface of the obtained sample.

This work was supported by a grant from the President of the Russian Federation (MK-2607.2022.1.2).

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G3-O-000604

LASER-INDUCED DESORPTION SPECTROSCOPY WITH AN ICP SOURCE — EXAMINATION OF TECHNIQUE APPLICABILITY FOR DETECTION OF RETAINED HYDROGEN*

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Development of remote diagnostic methods capable of measuring the content of hydrogen isotopes in the fusion-relevant materials is an important direction of plasma-surface interaction studies. Among these methods, laser-induced desorption spectroscopy (LIDS) [1–4] receives significant attention because of its non-destructive nature.

We have recently reported constructing a compact device with radiofrequency (RF) inductively coupled plasma (ICP) and equipping it with the 0.5-ms-pulse Nd:Glass laser and optical emission spectrometer for implementation of LIDS diagnostics. Here, we examine the conditions of LIDS technique applicability for diagnosing hydrogen-saturated metal layers.

A piece of Ti–V getter pre-exposed to deuterium atmosphere at 300°C for 24 h was used as a test sample. Optical emission spectra of plasma were measured for different values of laser pulse energy (2–25 J) with constant irradiated sample area of 1.1 cm^2. Background 13.56 MHz RF plasma was formed in argon gas (p_{Ar} = 10^{-3} mbar). The dependences of emission intensities of selected hydrogen lines (656 nm (Hα) and 486 nm (Hβ)) and argon lines (750 nm and 811 nm) on the laser pulse energy were analyzed. It was found that increasing laser pulse energy above certain value results in decrease of argon emission signal, which can be attributed to changes in electron energy distribution function caused by hydrogen release into plasma. Typical trends of 656 nm (Hα) and 811 nm (Ar) line intensities versus laser pulse energy are shown in Fig. 1.

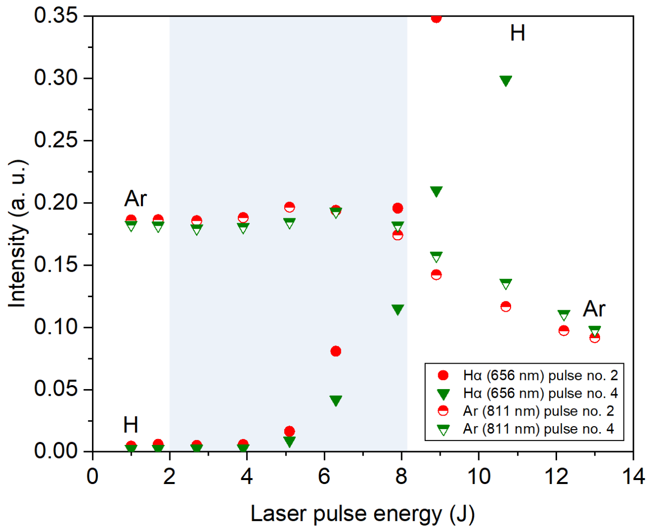

Fig.1. Relative intensities of 656 nm (Hα) and 811 nm (Ar) lines as functions of laser pulse energy.

As a result, the operating range of LIDS was determined both in terms of the laser pulse energy (2–8 J) and in terms of the Hα line intensity (which represents the amount of released hydrogen).

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DETECTION OF THE ANTIBIOTIC TRANSFORMATION UNDER LOW-INTENSITY e-BEAM RADIATION IN WATER

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The presence of pharmaceuticals in waste and natural waters has been of concern to environmentalists and researchers for several years, as their existence in aquatic systems leads to serious problems for living organisms. Sulfaguanidine (Figure 1) is a unique contaminant and is considered an emerging contaminant in water systems. It has been found in underground even drinking water in concentrations ranging from ng to μg/l. In a previous work, we investigated the photochemical behavior of a sulfanilamide antibiotic in aqueous solutions under the action of UV radiation from a KrCl excilamp [1, 2]. Some photoproducts have been detected using electron absorption and fluorescence spectroscopy. With regard to bacterial activity, these photoproducts exhibit greater toxicity than sulfaguanidine and exhibit higher inhibitory activity against E. coli and S. aureus cells [3].

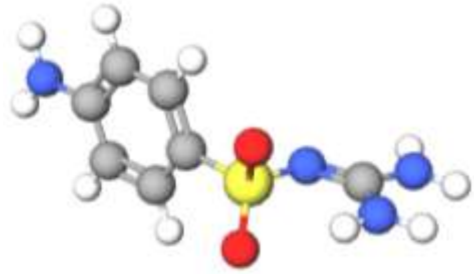

Fig.1. Structures of sulfaguanidine.

In this work, the transformation processes of sulfaguadinine in liquid solutions after e-beam irradiation in air was studied. The scheme of the experimental setup is described in detail in Ref. 4. The e-beam had the following parameters: a duration of 2 ns; an average electron energy of 170 keV; a current density of 130 A/cm2; a single pulse energy of up to 4.42 mJ/cm2; a change in the number of pulses is from 1 to 3000 (from 4.42 mJ/cm2 to 132.6 J/cm2). A gas discharge switch filled with nitrogen up to 38 atm is used to form high-voltage nanosecond pulses (see Ref. [5]). We monitored the conversion of sulfaguanidine by pulsed cathodoluminescence and steady state spectroscopy (absorbance and luminescence). The excitation of the aqueous solution and the recording of the cathodoluminescence spectrum were carried out simultaneously by the same pulse of the e-beam.

All details of changes in cathodoluminescence, absorption, fluorescence, fluorescence excitation and luminescence spectra of sulfagunidene in water will be reported in detail in the report. It is worth noting in conclusion that in contrast to the photochemical behavior, most sulfaguanidine products are almost completely inhibited by the e-beam.

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MEASUREMENT OF THE ENERGY FLUX ON A FLOATING AND BIASED SUBSTRATE IN THE DUAL HIPIMS PROCESS*

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The energy delivered to the substrate during magnetron sputtering has a very strong effect on processes such as diffusion, island growth, crystallization and phase transformations [1,2]. Therefore, the energy delivered to the growing film has a strong influence on its structure, elemental and phase composition, and physical properties [3–5]. This work is devoted to measuring the energy flux density on the substrate and the specific energy transferred to Al, Cr and Ti films during dual pulsed magnetron sputtering in a wide range of duration (5–100 microseconds), frequency (0.4–10 kHz) and amplitude (15–150 A) of discharge current pulses. The scheme of the experimental setup is shown in fig. 1.a. Fig. 1.b shows how the amplitudes of the discharge voltage and current pulses change in the case of the duty cycle regulation at fixed pulse duration. The experimental results show that a decrease in the duration of the discharge current pulses leads to an increase in the energy flux to the floating and biased (-100 V) substrate by 40–70% at a fixed average discharge power. In addition, the specific energy per unit volume of the deposited coating increases several times. The paper considers the reasons for the increase in the energy flux to the substrate and the specific energy delivered to the film.

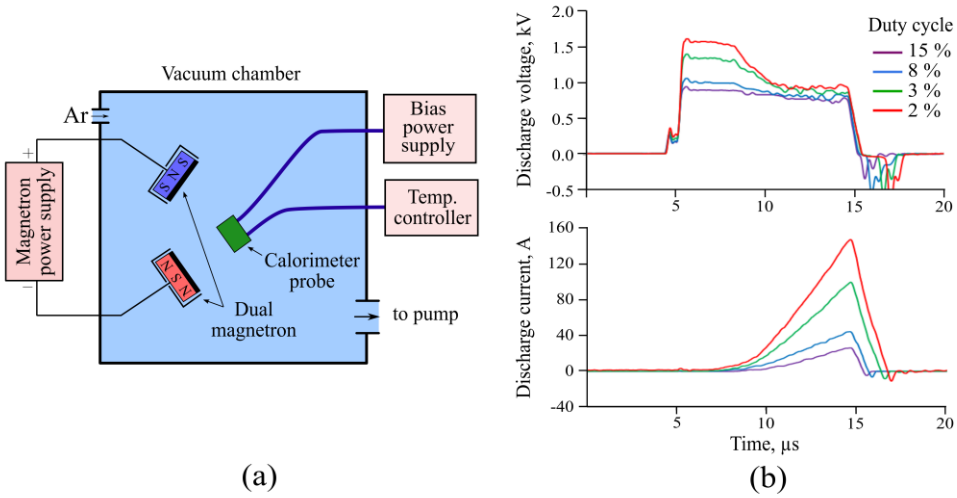

Fig.1. (a) scheme of the experimental setup, (b) discharge current and voltage pulses at various duty cycle values.

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INCREASING THE ELECTRICAL STRENGTH AND OPERATION STABILITY OF A SMALL-SIZED ION ACCELERATOR

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When developing a small-sized ion accelerator designed to generate neutrons [1, 2], special attention is paid to its electrical strength and operational stability. These parameters are negatively affected by dielectric inclusions, oxide films, and adsorbed gases on the surfaces of the high-voltage gap of the accelerating system of the ion accelerator. In particular, the presence of listed defects on the surface of the high-voltage electrode of the accelerating system lead to the emission processes occurrence in it and a decrease in the accelerator electric strength. At the same time, the presence of such defects on the accelerating system surfaces stimulates the occurrence of desorption processes in the accelerator volume due to the effect of elevated temperature and corpuscular flows. This leads to an increase in the residual gases pressure in the volume of the device and a decrease in the concentration of the working gas. It`s one of the reasons for the decrease in the neutron flux during the operation of the accelerator and the decrease in the stability of its operation [3].

One of the ways to improve the electrical strength and stability of the accelerator is to improve the technology of its manufacture, in particular, the use of ion-plasma processing method of the accelerating system parts along with traditional methods of cleaning parts in preparation for assembling the accelerator. Therefore, this work is devoted to studying the influence of the ion-plasma method of surface treatment of the ion accelerator accelerating system on its electrical strength and stability. To determine the necessary processing parameters, the dynamics of the discharge in an argon and the geometry of the processed electrodes of the accelerating system of the accelerator were simulated (Fig. 1). After that, the distribution of the ion current density on the accelerating system surfaces was studied and the time range of ion-plasma treatment was determined. As a result, the processing parameters were determined, which were used in the manufacture of the ion accelerator using improved technology. It is shown that the use of ion-plasma treatment in the manufacture of a small-sized ion accelerator makes it possible to increase its electrical strength and operational stability.

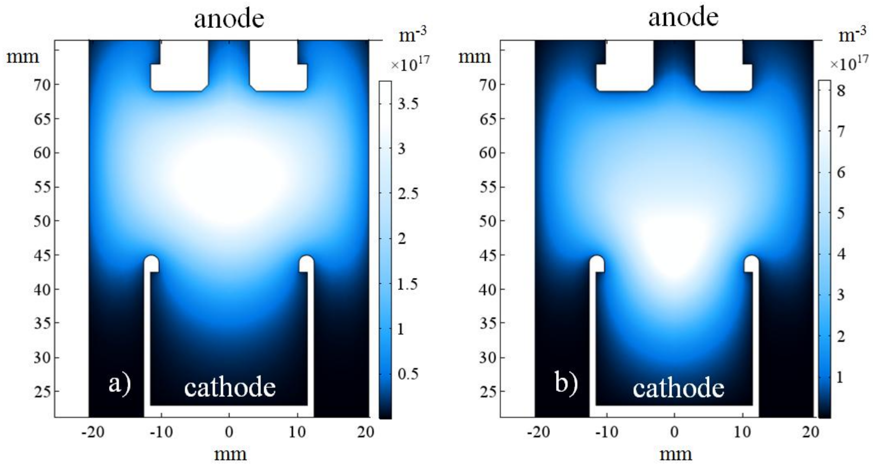

Fig.1. The density of excited argon atoms in the “anode-treated electrode (cathode)” system at a discharge voltage of 1 kV and a pressure of 0.06 Torr (a), at a discharge voltage of 400 V and a pressure of 0.1 Torr (b)

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EFFECT OF AN INTERMEDIATE CR/ZR AND MO/ZR BARRIER LAYER FORMED BY USING LEHCEB ON INTERDIFFUSION OF CR COATING WITH ZR SUBSTRATE

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Alloys based on Zr are widely used in modern nuclear power engineering due to a set of exceptional properties [1]. During normal use, Zr alloys form a protective layer of ZrO_2 that prevents corrosion. However, at high temperatures, which can occur under accident conditions, zirconium alloys exhibit poor oxidation kinetics. In a steam environment at a temperature above 860 °C, the intensity of the oxidation reaction increases, while it is additionally accompanied by the release of hydrogen and heat, and when 1200 °C is reached, it becomes self-sustaining [2–4]. The concept of emergency-tolerant fuel (ATF), which is currently being developed, defines several research and development strategies aimed at improving the safety of nuclear fuel during normal operation, transients, and possible accidents [4–6]. One of the ATF strategies is to use surface modification technologies to develop protective coatings on the surface of Zr [5, 6].

To date, Cr-based coatings are one of the promising candidates for the role of a protective material. However, mutual diffusion at the interface between the protective coating and the substrate is a serious problem. In addition, interdiffusion can degrade the adhesive properties of the coating, leading to the destruction or swelling of the coating. The easiest way to limit diffusion between the Cr plating and the Zr substrate is to add a diffusion barrier between the plating and the Zr substrate. Mo is considered as one of the possible materials for such diffusion barriers, since it has a CTE close to Cr, high thermal conductivity, a high melting point, and an acceptable neutron cross section. In this case, the potential eutectic phase Mo-Zr has a higher melting point (1550 °C) compared to Cr-Zr (1330 °C) [7, 8]. Therefore, this work is aimed at studying the effect of mutual diffusion between the Cr coating and the Zr substrate after the formation of an intermediate barrier layer of Cr/Zr and Mo/Zr using by LEHCEB.

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THE EFFECT OF LOW-ENERGY HIGH-CURRENT PULSED ELECTRON BEAM IRRADIATION ON THE STRUCTURE, PHASE COMPOSITION AND PROPERTIES OF Ni_3Al-TiC COMPOSITE

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Using X-ray diffraction, scanning and transmission electron microscopy we studied the effect of low-energy high-current pulsed electron beam (LEHCEB) irradiation with the energy density in the interval of 8 – 18 J/cm^2 on the structural characteristics, phase composition and tribotechnical properties of Ni_3Al-TiC composite with TiC content in the interval from 0 to 30 vol.% fabricated by self-propagating high temperature synthesis in the thermal explosion regime under pressure.

We showed that the synthesis of Ni_3Al intermetallide occurs practically completely when TiC content in the composite is 10 vol.% or less. Only insignificant amount of NiAl intermetallide (less than 4 vol.%) is measured. There are 16 and 15 vol.% of NiAl intermetallide and unreacted nickel, respectively, in the composite when TiC concentration increases up to 30 vol.%.

TiC particles are combined in clusters which size varies from several units to several hundred micrometers in the composite without LEHCEB irradiation. Each TiC particle is surrounded by the matrix material in small clusters while the particles are in contact with each other in the coarse clusters.

New phases do not form in the near-surface layer of the composite as a result of LEHCEB irradiation. NiAl intermetallide phase completely disappears in Ni_3Al-10 vol.% TiC composite. In Ni_3Al-30 vol.% TiC composite the unreacted nickel completely disappears and NiAl content in the matrix decreases down to 12 and 6 vol.% after LEHCEB irradiation with the energy density of 12 and 18 J/cm^2, respectively.

LEHCEB irradiation leads to the formation of wavy relief on the surface of the material (fig. 1 left). The surface roughness decreases with the increase of the energy density in the TiC-free material and vice-versa in the composites.

TiC particles of the initial size are not visible in SEM on the wave crests. There are a lot of dispersed particles of several tens of nanometers there (fig. 1 right). Remains of the original coarse TiC particles are in the dimples of the relief. They are surrounded with dispersed round-shape particles. Thus, LEHCEB irradiation leads to dispersion of the carbide phase, as well as to the increase in its content in the surface layer from 10 to 15 and from 30 to 45 vol.% in the composites with the initial TiC content of 10 and 30 vol.%.

LEHCEB irradiation of the material results in the increase of microhardness. The microhardness of TiC-free material and composites Ni_3Al-TiC with 10 and 30 vol.% of TiC increases by 32, 35 and 49 %, respectively. The reasons for the microhardness increase are the matrix grain size refining, the internal stress appearance, phase composition evolution (the decrease of Ni and NiAl and the increase of TiC content) and TiC particles refining in the near-surface layer of several micrometers in depth.

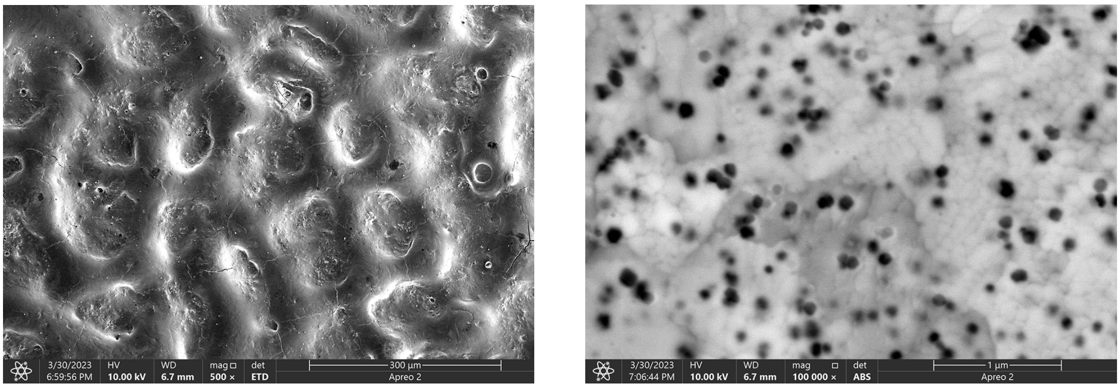

Fig.1. SEM images of Ni_3Al-30 vol.% TiC processed with LEHCEB.

This work was funded by Russian Science Foundation, grant No. 23-29-00673, https://rscf.ru/project/23-29-00673/.

INVESTIGATION ON THE PROPERTIES OF ANODIC OXIDES GROWN ON ALUMINIUM-SILICON ALLOYS IRRADIATED BY PULSED ELECTRON BEAM

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Al-Si alloys are among the most common aluminium based materials for cast products due to their high strength-to-weight ratio, excellent processability and relatively low cost. The presence of Si in the molten Al phase improves the castability and decreases the solidification shrinkage; the wear behavior and corrosion resistance are augmented as well due to the presence of silicon. Hard anodic oxidation is largely employed to improve their surface mechanical properties and corrosion resistance. However, the presence of Si, especially in eutectic and hypereutectic alloys, makes the process difficult or even not possible [1].

The pretreatment of Al-Si alloys with intense pulsed electron beams can effectively overcome the aforementioned limitation [2,3]. Electron beam sources can be employed to refine and disperse Si particles and effectively create supersaturated solid solutions that are more amenable to oxidization.

In the present work, two electron beam equipments were used, RITM-SP and SOLO, to pretreat the surface properties of *hypoeutectic*, *eutectic* and *hypereutectic* Al-Si alloys, by investigating the effect of energy densities and number of pulses. The electron beam treated substrates were hard anodized by investigating the effect of current density and anodic oxidation duration. Samples were characterized in term of microstructure, element distribution, thickness of the electron beam modified layers and of the anodic oxides, and surface mechanical properties.

Figure 1 shows the EDS elemental maps of the cross sections of anodic oxide coatings grown (a) on the untreated AlSi7 alloy, (b) after electron beam treatment with RITM-SP at 3.3 J/cm^2 per 16 pulses (3.5 μs each) and (c) with SOLO at 30 J/cm^2 per pulse (200 μs). Oxides formed on EB modified alloys appear to be more homogeneous and compact.

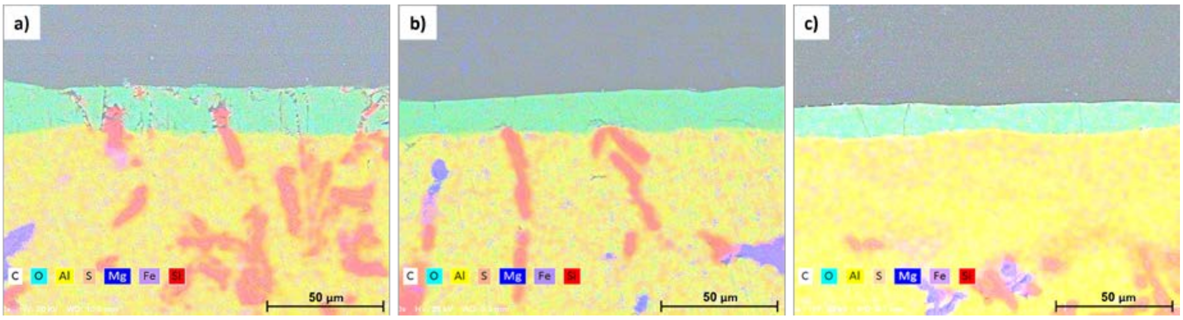

Fig 1. Cross sectional EDS maps of anodized AlSi7 alloys: untreated (a) and electron beam treated, RITM-SP (b) and SOLO (c).

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TRIBOLOGICAL PROPERTIES OF INTERMETALLIC COATINGS OF THE TI-AL SYSTEM ON TITANIUM ALLOY TI6AL4V

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Titanium and its alloys have found application as structural materials of aviation and space technology, they are also used in some areas of mechanical engineering [1]. In spite of this, the problem of intensive wear of titanium alloys surface when working in friction pairs with the majority of materials is still not solved. The addition of lubricants does not eliminate friction setting [2], so surface hardening technologies based on ion-plasma treatment of parts are used to improve the wear resistance of titanium alloys. During dry friction, the temperature of the rubbing surfaces can reach 800ºC, and in the case of titanium alloys, due to their low thermal conductivity, the temperature in the contact zone can be higher [3]. Such heating causes structural and phase changes in the base material, promotes intensive oxidation of surface layers, contributes to their pitting and increased wear of parts. Thus, the hardened layers in addition to wear resistance must have resistance to oxidation at high temperatures. Both of these conditions are satisfied by intermetallic compounds of the Ti-Al system [4,5].

We study the tribological properties of intermetallic coatings of the TiAl system obtained by ion-plasma treatment of an aluminum coating on a Ti-6Al-4V alloy. It has been established that a decrease in the thickness of the initial aluminum coating from 2.5µm to 0.5µm reduces the fraction of the $TiAl_3$ phase in the resulted coating. This promotes the formation of hardened layers, which consist mainly of the TiAl phase and the Ti(Al) solid solution and provide high wear resistance of the coated Ti-6Al-4V alloy.

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EFFECT OF BIAS VOLTAGE DURING PLASMA-ASSISTED HF-SPRAYING OF ALMGB$_{14}$ POWDER TARGET

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This paper presents the results of studying coatings of the composition $AlMgB_{14}$. Coatings obtained by plasma-assisted RF deposition from powder materials. The system consists of a target with a diameter of 200 mm with a powder material and a PINK gas plasma generator. The system makes it possible to reduce the coating pressure, significantly increase the coating rate and control the properties of the applied coatings due to plasma assistance in the deposition process. The studies were carried out on the installation of electron-ion-plasma surface engineering "COMPLEX", developed in the laboratory of plasma emission electronics of the IHCE SB RAS.

Coatings of $AlMgB_{14}$ composition obtained by plasma-assisted RF deposition in vacuum were studied. All data were obtained for five test samples of AlMgB14 coatings, one test sample of $AlMgB_{14}$+30%TiB_2 coating, and one test sample of $AlMgB_{14}$+70%TiB_2 coating.

As the bias potential increases, the mechanical properties of the coating may deteriorate. Due to the increase in the energy of the arriving atoms of the sputtered target on the sample surface, the adhesion to the sample surface will increase. In this case, the growth rate of the coating will greatly deteriorate due to bombardment with inert gas ions. This entails an increase in the coating time, an increase in the cost of the coating process, and a deterioration in the surface morphology.

Based on the developed technological methods of high-frequency ion-plasma deposition with a bias voltage of 100 V and a deposition duration of 3 h, coatings based on $AlMgB_{14}$ and $AlMgB_{14}$-TiB_2 were deposited on substrates made of hard alloy grade VK8, steel grade 12Kh18N10T, aluminum alloy grade 1550 and titanium alloy brand VT1-0.

Optical and scanning electron microscopy was used to study the structure of the resulting coatings depending on the bias voltage applied to the substrate.

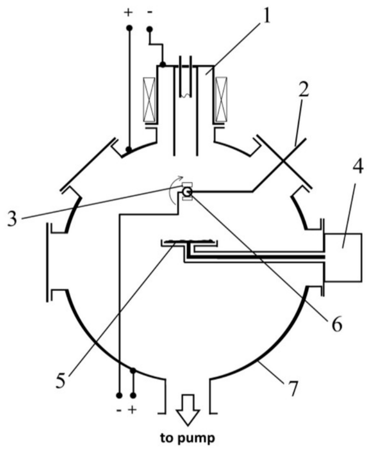

Fig.1. Scheme of the experiment.

The study was supported by a grant from the Russian Science Foundation no. 19-19-00183, https://rscf.ru/project/19-19-00183/

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SPUTTERING OF AMORPHOUS Si AND SiO_2 BY LOW-ENERGY Ar^+, Kr^+ AND Xe^+ IONS

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In modern microelectronic technology, the transition to the atomic scale era requires localizing ions' impact within one atomic layer. This could be achieved through application of ions with energies to be of the order of atoms' binding energy (5-50 eV) into manufacturing process as, for example, PEALE (Plasma Enhanced Atomic Layer Etching) [1,2] and PEALD (Plasma Enhanced Atomic Layer Deposition)[3,4].

Nevertheless, there is a sufficiently extensive set of data on the sputtering of different materials by different types of ions [5] at present, there are almost no reliable and sufficiently correct data on ion sputtering yield (is the probability of a target atom to leave the surface per coming ion with kinetic energy) at ion energies below 100 eV, even for such important materials for microelectronic applications as Si and SiO_2.

In this work, the sputtering of thin films of amorphous Si and SiO_2 by low-energy Ar^+, Kr^+, and Xe^+ ions in the range of 20–200 eV was studied in low-pressure ICP plasma in pure Ar, Kr, and Xe, respectively. Sputtering rate measurements were made in-situ with a laser ellipsometer, while various plasma diagnostics were used to accurately determine the composition, energy spectrum, and ion flux onto a sample surface. The surface modification of Si films during sputtering was determined by ex-situ surface diagnostics: vacuum Atomic Force Microscopy (AFM) and angular X-ray Photoelectron Spectroscopy (XPS).

It was shown that sputtering still preserves at ion energies below the kinetic sputtering threshold. However, the yields on ion energy dependencies drastically changes at the energy of about 75 eV (fig. 1). The AFM analysis shown, that low energy spattering causes a significant decrease of the samples' roughness. The XPS data demonstrated, that even 200 eV ions able to penetrate rather deep into the materials, producing highly damaged and, thus, abounding vacant chemical bounds top layer, and accumulating at a depth of 3-4 nm from the surface.

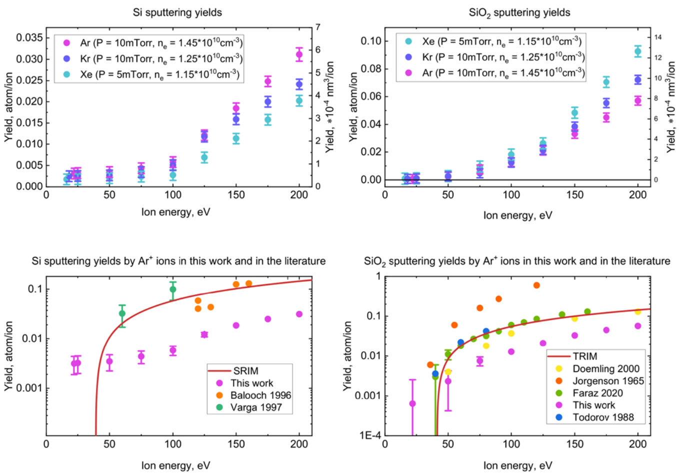

Fig.1. Sputtering results for Si and SiO2.

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PLASMA ENHANCED ATOMIC LAYER ETCHING IN Ar/C_4F_8 INDUCTIVELY COUPLED PLASMA WITH O_2 CLEANING STEP*

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Atomic layer etching (ALE) is a technique for cyclical removing thin layers of material (one to several atomic layers per iteration) using sequential steps of (almost) self-limiting reactions [1,2]. As an alternative to continuous etching, ALE provides significantly higher accuracy, producing much less roughness on the resulting surface and almost no contamination of the material. Moreover, ALE able to reduce existing roughness, which could be applied as inter-step polishing [3,4].

Every ALE cycle consists of at least two self-limiting sequential steps: modification of the surface and removal of modified layer [1–3]. In Plasma Enhanced ALE the removal step is almost always sputtering by a noble gas' ions, while the modification step is deposition of chemical radicals, bounding only with the first atomic layer of material or forming a thin film on the surface. During modification, the reagent could be deposited on the chamber's walls. Such a contamination increases the total amount of chemical compound in the chamber and creates a source of radicals during the sputtering, which violets repeatability of the process from step to step and could even convert PEALE to RIE.

Considering all the above, in this work we have found PEALE recipes, consisting of three principal steps: deposition of fluorocarbon film from C_4F_8-plasma, sputtering by Ar^+ ions and O_2-plasma cleaning. The experiments were conducted in an ICP-chamber, manufactured by JSC «Research Institute of Precision Machine Manufacturing». Sputtering rate measurements were made in-situ with a laser ellipsometer, while various plasma diagnostics were used to accurately determine plasma parameters and chemical composition of the discharge. The resulting recipes show unprecedented repeatability and precision (fig. 1.: 3 atomic layers per cycle regime was repeated 20 times, the other two 40 times).

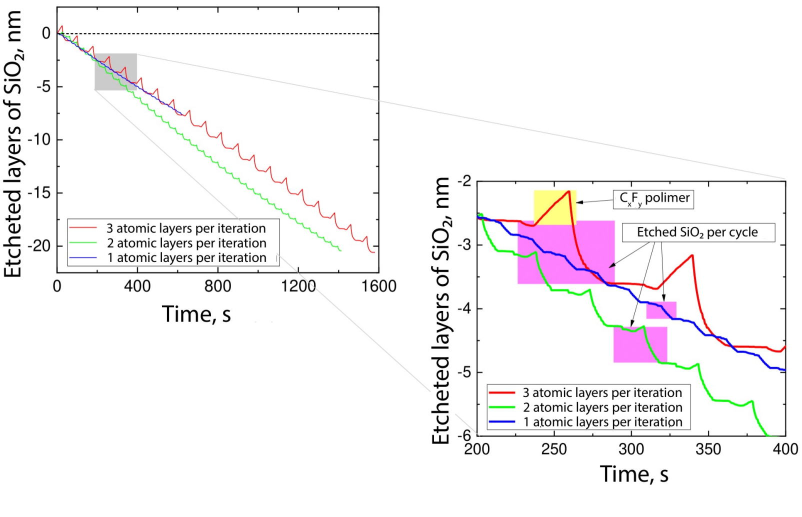

Fig.1. Resulting PEALE recipes.

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NANOPARTICLES FABRICATION IN HIGH-ENTHALPY PLASMA FLOW AND COVERING THEM ON A SURFACE

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The work is devoted to the study of the interaction of a high-enthalpy plasma flow of complex compounds with surfaces. The source of the plasma flow was a pulsed disk MHD accelerator [1], which made it possible to obtain plasma streams of various compositions flowing into a vacuum. Thus, in the case of using methane as a plasma-forming gas, the following parameters of the accelerated flow were obtained: velocity at the exit of the accelerator was 5 km/s, static pressure about 1 kPa, static temperature 3000 K, and electron density about 10^{16} sm^{-3}. Discharge duration was 48 ms, methane consumption was 0.12 mole. Coatings were formed when methane plasma flowed onto the surface. Covering properties are described in [2-3]. The acceleration of a mixture of methane and monosilane in argon led to the formation of a silicon carbide coating of various morphologies.

Modernization of the accelerator made it possible to obtain plasma flows of a complex composition by introducing volatile precursors with a low boiling point, for example, titanium tetrachloride, into the prechamber of the accelerator. A mixture of nitrogen and hydrogen with the addition of a small amount (up to 10%) of $TiCl_4$ includes a titanium covering of various morphologies [4]. We obtain a smooth coating deposited from the gaseous phase by placing the substrate near the accelerator exit. Titanium nanocrystals deposit on a surface in case the substrate is set at a distance of more than 140 mm from the outlet. The experiments made it possible to conclude that the condensation of substances with a high boiling point begins in an initially homogeneous freely expanding plasma stream, at a certain distance from the accelerator. For example, the titan condensation in our case. Possible formation and condensation of chemical compounds, such as silicon carbide. The coating of nanosized particles becomes feasible due to the dispersion of the transport gas (mixture of H_2 and N_2) in the surrounding pumped volume. In this case, the formed particles continue to move by inertia in the direction they received during condensation. The density of the gas flow becomes insufficient at the location of the streamlined surface for the taking away of nanoparticles. Further, nanosized formations move at a speed of about several kilometers per second and collide with the surface.

The purpose of the work is to obtain experimental data for building a physical model of the ongoing processes and developing new coating deposition methods. The report describes methods for measuring plasma parameters and analyzing the properties of the obtained coatings. A comparison of launch parameters, condensation condition, and deposition structure in different experiments is given. A mixture of methane and argon, methane and monosilane, nitrogen and titanium chloride, and nitrogen and boron bromide were used for coatings formation.

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GENERATORS FOR HIGH-VOLTAGE ELECTRIC PULSE CRUSHING OF MATERIALS DEVELOPED AT THE INSTITUTE OF HIGH CURRENT ELECTRONICS*

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Technology based on the use of high-voltage high-current electric discharge in a liquid medium (electrodischarge technology) is being actively and successfully studied as an alternative to traditional mechanical methods for the destruction and grinding of materials [1]. The critical element of the technology is the high-voltage repetitively pulsed generator. The generator parameters must meet high requirements: the voltage pulse rise rate is about 10^{12} V/s at an amplitude of about 10^5 V, the discharge current amplitude is about 10^3–10^4 A, the time constant of the discharge circuit is about 10^{-7}–10^{-6} s, and the pulse repetition rate is about 1–10 Hz. At the stage of developing the fundamentals of the technology of electric discharge destruction of materials, the generation of high-voltage pulses was mainly based on the use of a multi-stage circuit of the Arkadiev-Marx generator. Such generator is relatively reliable, but have low specific characteristics. For the production implementation and optimization of the electrical support of the technology, it is important to develop alternative technical solutions for generating high-voltage pulses that provide a significant improvement in the specific energy, weight and size characteristics of the equipment. From this point of view, generators based on transformer circuits in many cases turn out to be preferable to Arkadiev-Marx generators.

For many years, the Pulsed Power Department of the Institute of High Current Electronics has been conducting research on the development of generators for high-voltage electric pulse crushing technology [2]. This work describes such generators developed in recent years using transformer circuits. Two approaches are considered. The first one is generators based on pulsed charging of a high-voltage capacitive storage from the primary low-voltage capacitive storage through a step-up pulse transformer. The second approach is based on the use of a linear pulse transformer circuit. This transformer circuit, which is successfully used in high-power electrophysical generators in modes with single pulses [3], was adapted for repetitively pulsed operation. A series of generators with full automation of control, with an output voltage level of up to 400 kV and a stored energy of up to more than 1 kJ, has been developed, which make it possible to vary the amplitude of the output voltage, the energy of the electric discharge, and the pulse repetition rate over a wide range. Generators are used to crush materials, but other technological applications are possible.

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* The work was carried out within the framework of the state assignment of the Ministry of Science and Higher Education of the Russian Federation on the topic No. FWRM-2021-0001

VTI-4 ALLOY OXIDATION PROTECTION BY CATHODIC ARC DEPOSITION OF CR-AL+Y-AL-O COATING

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Ti-Al group intermetallic alloys are gradually gaining wider use in industry due to the combination of low density, good mechanical characteristics at high temperatures and oxidation resistance. High specific strength and modulus of elasticity allow the use of these alloys in the production of turbojet engines, stationary turbines, as well as for the production of turbocharger rotors in the automotive industry.

However, the use of such alloys in high temperature environment requires additional corrosion and oxidation protection to suppress the formation of unstable TiO_2 oxide film on the alloy surface [1]. One method of protection of Ti-Al alloys is the application of protective overlay coatings such as intermetallic and ceramic. These coatings prevent oxygen diffusion to the alloy and form on the surface stable oxides like α-Al_2O_3 [2].

In this work we propose a method of protection of alloy VTI-4 (Ti—11Al—40Nb) against high-temperature corrosion by deposition a two-layer coating consisting of an intermetallic sublayer of Cr-Al system considered in [3], and an external ceramic layer of Y-Al-O system. For crystallization of coatings after deposition of each layer a vacuum heat treatment was carried out. Each coating layer was annealed in vacuum furnace since as-deposited coating had amorphous structure.

The obtained samples with two-layer coating were tested for heat resistance in the furnace and by thermal cycling at a temperature of 750 ^{O}C, exceeding the limit operation temperature of the alloy. The results show that the coating did not spall after thermocycling tests and after oxidation in furnace, the weight of the samples after exposure in the furnace did not change significantly.

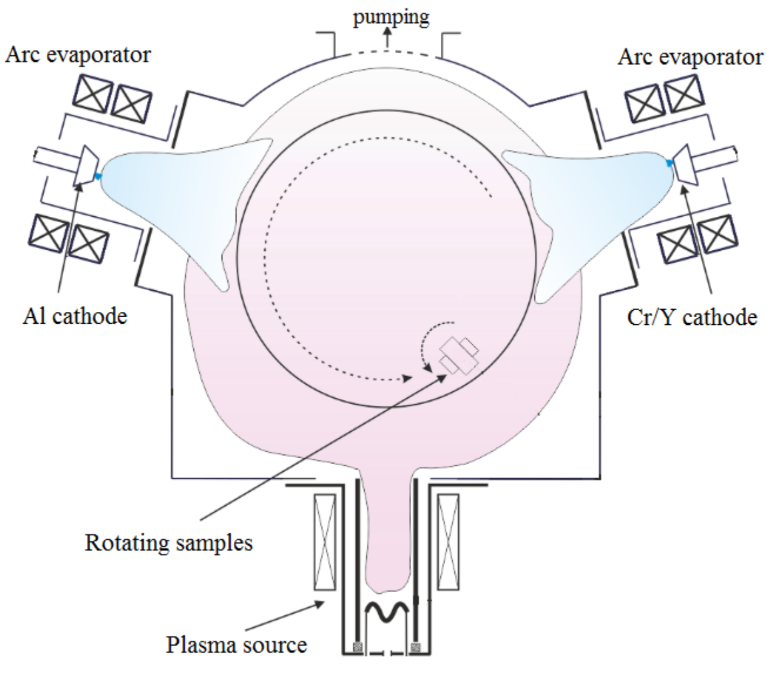

Fig.1. Deposition scheme.

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$MoSi_2$- and $ZrSi_2$-BASED COATINGS DEPOSITED BY MAGNETRON SPUTTERING OF HETEROPHASE CERAMIC CATHODES IN HIPIMS REGIME

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Promising materials for the manufacture of high-temperature coatings are $MoSi_2$ and $ZrSi_2$ [1]. Their high oxidation resistance is due to the formation of a surface SiO_2 layer when exposed at high temperatures [2]. The introduction of boron into the composition of coatings reduces the viscosity of the surface layer of SiO_2 and increases oxidation resistance [3]. In previous study of $MoSi_2$-based coatings obtained by direct current magnetron sputtering (DCMS), it was shown that Mo-Zr-Si-B coatings surpass Mo-Si-B in crack resistance, thermal stability and oxidation resistance due to modification of their structure [4]. In turn, the introduction of $MoSi_2$ into the composition of coatings suppresses the t-ZrO_2 → m-ZrO_2 transformation, which causes cracking of the coating [5]. For microcrystalline coatings $ZrSi_2$-$MoSi_2$-ZrB_2, high oxidation resistance is associated with the formation of SiO_2, ZrO_2, and $ZrSiO_4$ top films [6].

High power impulse magnetron sputtering (HIPIMS) method provides a high plasma density of up to 10^{14} ions/cm^3 (for DCMS: 10^{10} ions/cm^3), as a result of which the atomized atoms are intensively ionized when passing through the plasma, and the flow consists mainly of ions, not atoms, as in the case of DCMS [7]. An increase in the ion/atom ratio in the flow leads to an increase of adhesion, hardness, wear and oxidation resistance of deposited coatings [8].

The purpose of this work was to study the structure and properties of oxidation-resistant nanostructured Zr-Mo-Si-B and Mo-Zr-Si-B coatings obtained by HIPIMS using heterophase targets.

The ($ZrSi_2$-ZrB_2-$MoSi_2$)/Cr and ($MoSi_2$-MoB-ZrB_2)/Mo functionally-gradient targets were manufactured using self-propagating high-temperature synthesis and hot pressing. The coatings were applied on a UVN-2M type installation equipped with source for ion cleaning, 2 magnetrons and Trumpf TruPlasma 4200 power supply. The frequency varied in the range from 100 to 1000 Hz, the peak current at an average power of 1 kW was from 70 to 100 A. Sputtering was carried out in Ar at a pressure of 0.1-0.5 Pa. The composition and structure of the coatings were studied using scanning and transmission electron microscopy (SEM and TEM), energy dispersion spectroscopy (EDS), glow discharge optical emission spectroscopy of (GDOES), X-ray diffraction (XRD). The mechanical properties of the coatings were determined on the CSM Nanohardness Tester by the method of nanoindentation. In order to determine the oxidation resistance of the coatings, annealing in air was carried out in muffle furnaces SNOL-7.2/1200 and TC 15.1800.DM.1F at 1000-1700 ° C and subsequent SEM, EDS, GDOES, and XRD studies.

The results showed that the targets were characterized by a density of at least 95%, hardness >10 GPa and successfully operated in HIPIMS regime, withstanding thermal cycling conditions: 0→70→0 kW. As a result of long-term operation, a network of microcracks was detected on the surface of the working layer, but the integrity of the target was not violated. All the coatings obtained had a dense, low-defect structure with a uniform distribution of elements in thickness and a low level of impurities. Columnar grains typical of single-phase ion-plasma coatings are not observed. The coatings in most cases were nanostructured or X-ray amorphous. The hardness was over 20 GPa, and a clear correlation was established between the energy parameters of HIPIMS, internal compressive stresses and mechanical characteristics of coatings. The coatings were highly resistant to oxidation at temperatures of 1000-1500 °C, which was associated with the formation of protective surface layers based on borosilicate glass with dispersed inclusions of Zr-containing oxide phases that prevent oxygen penetration deep into the coatings during high-temperature heating in air.

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MOLECULAR MOBILITY IN NEAR-SURFACE NANO-LAYERS OF ULTRA-HIGH-MOLECULAR -WEIGHT POLYETHYLENE AS REVEALED BY THERMOLUMINESCENCE ACTIVATED BY LOW-TEMPERATURE PLASMA

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It is known that the behavior of bulk materials depends dramatically on the properties of surface and near-surface layers. This work is concerned with a study of molecular mobility in the near-surface nano-layers of the ultra-high molecular weight polyethylene (UHMWPE) reactor powders (RP) and its change after compaction at room temperature and subsequent sintering at the higher temperature close but lower than melting temperature.

Interest in these characteristics is caused by currently actively developing non-solvent (dry) methods for processing UHMWPE into high-performance fibers, alternative to gel technology using a large amount of solvents. Mechanically coherent film obtained by compaction/sintering is a precursor for subsequent orientation hardening (orientation drawing), which makes it possible to obtain high-strength high-modulus fibers. The precursor should not break prematurely along the weak grain boundaries before reaching the ultimate draw ratio.

Obviously, the properties of the surface of the powder particles play a key role in the formation of strong intergrain boundaries. The molecular mobility of the near-surface layers was studied by thermoluminescence method using self-made device Nanoluminograph, patented in Russia and USA [1-2]. The surface of the investigated samples was activated by low temperature, low power high-frequency (HF 13.36 MHz) plasma of Ar gas discharge at 77K. When experiments are carried out in given conditions (the consumed energy $W = 0.004$ Wt/cm^3, activation time 1 sec, Ar pressure is 10^{-1} torr, reduced strength is $E/P \sim 2\cdot10^3$ Vcm^{-1}/MPa, electron energy is $Ee \approx 50$-100 eV) the thickness of the analyzed surface layer d is about 5-10 nm. It was recognized that the peaks on glow curves (the dependence of thermoluminescence intensity on temperature) are associated with recombination of the stabilized charge carriers in the temperature range of relaxation transitions in polymers due to releasing molecular mobility in the immediate vicinity of the charge traps, which can be of various nature and depth [3-4].

The glow curves were recorded by Nanoluminograph for UHMWPE powders, compacted and sintered samples. As an example, the powder and compact glow curves are presented in Fig. 1A. The complicate profile of glow curves implies the overlapping of a number of different elementary relaxation processes. Profile curve analysis using the Fityk program allows us to obtain information about possible elementary relaxation processes (Fig. 1B and 1C). The change in molecular mobility (defreezing molecular motion in the temperature range of relaxation processes) after compaction and sintering will be discussed.

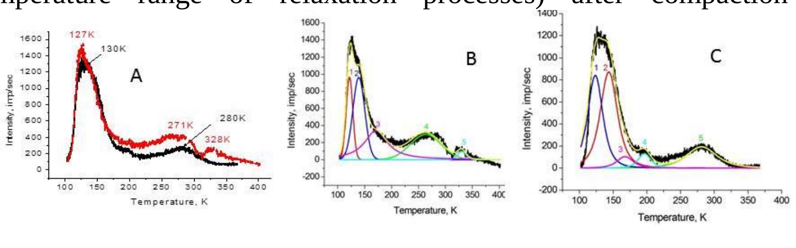

Fig.1. Powder glow curve (black) and compact powder glow curve (red) (A); decomposition of the compact glow curve (B); decomposition of the powder glow curve (C)

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SYNTHESIS OF THE YSZ-BASED COATINGS BY ELECTRON BEAM AT FOREVACUUM PRESSURES

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Ceramic coatings have been widely used in modern technological industries [1]. A special place is occupied by coatings based on zirconium ceramics, which have a hardness of up to 10 GPa, remarkable temperature and corrosion resistance, low thermal conductivity, and consistently high thermal expansion coefficient, mechanical and dielectric properties [2]. The most relevant application of these coatings is their use as thermal barrier coatings for parts of items and devices subjected to high cyclic thermal loads [3]. Despite the availability of numerous methods for synthesis of such zirconium coatings [4], electron-beam synthesis allows one to achieve the best coatings characteristics that meet modern requirements [5].

Our work presents a method for the synthesis of coatings based on zirconium ceramics partially stabilized with yttrium oxide using a forevacuum plasma-cathode electron source operating in the fore-vacuum (1-100 Pa) pressure range. The main feature of this method is the effective interaction of the electron beam with the surface of evaporating dielectric due to surface charge neutralization by positive ions from dense beam-produced plasma. This effect finally results in high deposition rates of ceramic coatings and their remarkable performance characteristics [6].

Figure 1 shows the scheme of the coating synthesis experiment, a photograph of the coating itself and its profile demonstrating high thickness (around 200 μm).

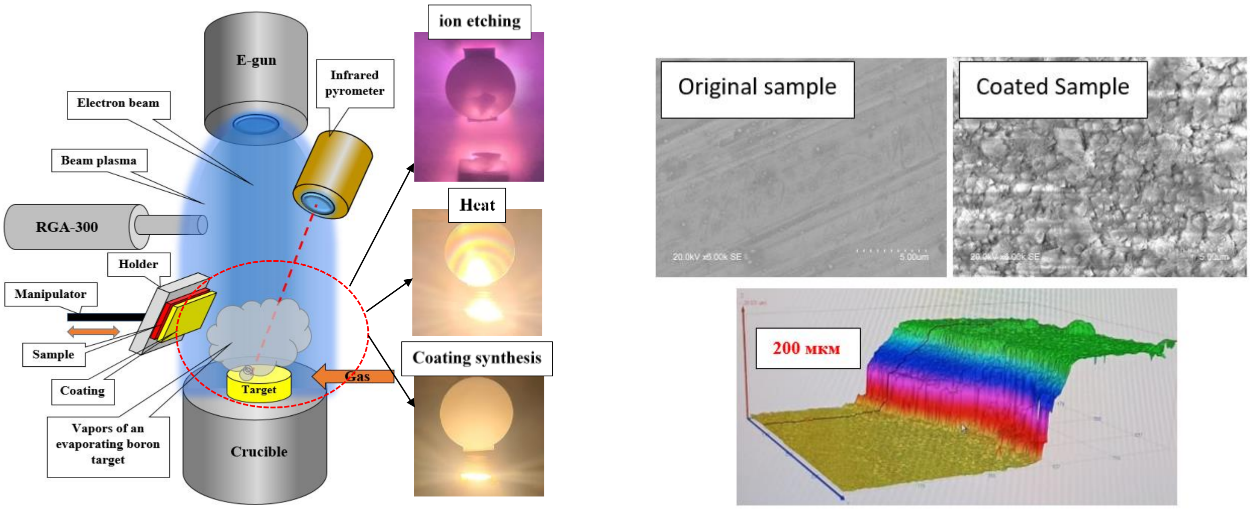

Fig.1. Experiment schematic (left), photographs of the original sample and the coated sample with the coating thickness (right).

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PLASMA DYNAMIC SYNTHESIS OF METAL OXIDES IN CO_2 MEDIUM *

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The accumulation of greenhouse gases in the atmosphere, in particular carbon dioxide CO_2, negatively affects the planet's climate change and necessitates the development of fundamentally new approaches to handling them. Carbon dioxide (CO_2) is the most spread greenhouse gas of anthropogenic origin, the concentration of which in atmosphere has increased by 47% since the industrial revolution [1,2]. The importance of reducing CO_2 emissions and/or its recycling is widely recognized to prevent global warming and its consequences.

At present, methods for CO_2 utilization are being actively developed and implemented. Most of them are based on carbon dioxide capture and storage, while technologies for processing CO_2 to produce value-added products can be more favorable. Up to date, there are several potential approaches for direct carbon dioxide applying including its addition to the reservoir for enhanced oil recovery [3], addition to carbonated drinks and food products, filling fire extinguishers [4].

At the same time, only in the last few years, annual CO_2 emissions have reached ~40 Gt [5], so the disposal of such volumes only by direct application looks very problematic. In this regard, there is also an increased attention to indirect utilization ways, which include the CO_2 conversion into chemicals, materials and fuels through chemical and biological processes [6]. The key problem of these methods is the need to break the bonds of the CO_2 molecule that requires a large amount of energy [7]. This is the main limiting factor for such technologies.

To minimize energy consumption and reduce the cost of ongoing processes, several approaches are considered: 1) the use of energy-intensive processes, where energy must come from carbon-neutral sources; 2) the application of catalysts to reduce the CO_2 activation energy; 3) reaching high temperatures or pressures to weaken the stability of CO_2 molecules [8]. The latter approach includes the use of plasma technologies, most of which focus on converting CO_2 to liquids or gases and do not consider the production of crystalline products that seems to be possible when applying CO_2 as gaseous precursor

Thus, the aim of this study was to utilize carbon dioxide by means of a high-speed electroerosive arc discharge plasma and produce useful value-added products in the form of dispersed materials. For this, the plasma dynamic method was implemented in the Cu-O, Fe-O, Ti-O and Al-O systems using CO_2 as a precursor, which made it possible to synthesize the corresponding micro- and nanodispersed metal oxides with a CO_2 conversion of up to ~15%. In addition, the different operation modes were considered to enhance the process efficiency and the possibility of using the synthesized ultrafine materials as a raw material for obtaining functional bulk materials was demonstrated.

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LOW-TEMPERATURE ION NITRIDING OF TITANIUM ALLOYS

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Ion nitriding is effective method of titanium alloys surface modification. It allows to reach a high saturation rate by nitrogen atoms and to obtain purposefully controlled structure and me-chanical properties of surface layer. Also process can be carried out at relatively low tempera-ture that protects a structure of core material, taking into account the specific operating condi-tions of the part [1-5].

The work is devoted to study of influence of the low-temperature ion nitriding of Ti-6Al-4V titanium alloy in non-self-maintained high-current arc discharge and in glow discharge at various process parameters on the diffusion layer growth rate and surface residual stress forces.

the regimes of processing of titanium alloys are determined, which ensure the production of hardened layers of the required thickness and quality in order to form residual surface stresses while maintaining mechanical characteristics.

As a result of this study, it was established that nitriding in both a non-self-maintained high-current discharge and glow discharge at a temperature of 450°C leads to increasing of the surface microhardness of titanium alloy Ti-6Al-4V samples up to 1.2 times.

Found that nitriding in a glow discharge at temperatures of 450, 500 and 600°C leads to formation of diffusion layer with case depth of 10, 13 and 17 microns, respectively. After nitrid-ing in a non-self-maintained high-current discharge at temperatures of 450, 500 and 600°C dif-fusion layer case depth increases and amounted to 17, 20 and 28 µm, respectively.

Temperature affects the sign and magnitude of the residual stresses. After ion nitriding in a non-self-maintained high-current discharge at a temperature of 600 °C, the magnitude of residual stresses is +12,4±10 kgf/mm2. After nitriding in a glow discharge at a temperature of 450 °C the magnitude of residual stresses is -23,7±10 kgf/mm^2.

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G3-O-010301

THE EFFECT OF THE CURRENT DENSITY ON THE STRUCTURE, COMPOSITION, AND PROPERTIES OF COATINGS FORMED IN THE SHORT-PULSE MODE OF MICROARC OXIDATION

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Microarc oxidation is a type of electrochemical surface treatment, similar in mechanism to anodizing. The difference is that surface micro-discharges are involved in the formation of the coating. High temperatures develop in the breakdown zone according to various sources at least 2000 °C and pressure (up to 600 Atm) [1, 2], conditions that ensure the formation of an oxide-ceramic coating on aluminum, titanium, and magnesium alloys. MAO coatings obtained in short-pulse mode are increasingly being used in practice [3], therefore, the study of the influence of various characteristics on the process of formation of MAO coating is relevant.

The paper presents the results of a study of the current density influence on the structure, composition, and properties of the MAO coating. MAO was performed at electrical parameters: U = 600 V, τ = 200 μs, f = 100 Hz on samples made of aluminum alloy 5052 with different surface area - 5, 10, 25 and 50 dm^2. It is shown that the change in the amount of energy in the microplasma discharge zone (MPD) per unit surface – current density, affects the structure and distribution of the coating composition over the treated surface. An increase in the current density from 42 A/dm^2 to 118 A/dm^2, when the coating area is constant, and the amount of MPD energy increases due to a more powerful power source, reduces the MAO time and increases the content of the crystalline phase - $FeAl_2O_4$ in the coating over the entire treated surface (Fig.1). A decrease in the current density from 118 A/dm^2 to 82 A/dm^2, when the area of the coated surface increases, and the amount of MPD energy is constant, leads to an increase in the MAO time and reduces the content of the crystalline phase - $FeAl_2O_4$ in the center of the treated surface, which leads to a change in the properties of the MAO coating on the surface of the treated aluminum alloy from the center to edge: with an increase in MPD energy per surface unit, the microhardness of the coating increases from 360 HV to 400 HV in the center of the surface and from 480 HV to 510 HV at the edge. As the coating area increases, the microhardness decreases from 500 HV to 300 HV in the center of the surface and from 560 HV to 460 HV at the edge of the treated surface.

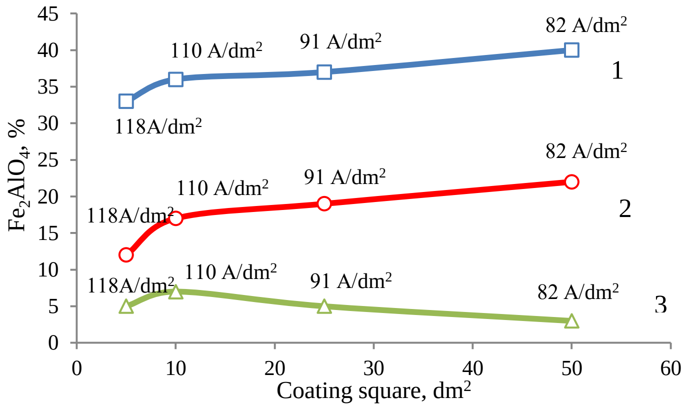

Figure 1. Distribution of $FeAl_2O_4$ spinel on samples with area of 5, 10, 25, 50 dm^2, with change in current density/

1 – edge, 2 – middle, 3 - center

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G3-O-010901

DEPOSITION OF THIN FILMS OF SOLID ELECTROLYTE LIPON IN A VAPOR-GAS MEDIUM (LI_3PO_4/Ar-N_2) ACTIVATED IN A LOW-PRESSURE ARC.

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Thin films of solid-state lithium-ion electrolytes are promising for use in small-sized autonomous power sources, elements of micro- and nanoelectronics. The high rate of vacuum-plasma synthesis (~0.5 μm/h) of lithium phosphor-oxynitride (LiPON) films with ionic conductivity of $\sim 2*10^{-6}$ $(Ohm*cm)^{-1}$ is provided by the method of anodic evaporation of Li_3PO_4 in a low pressure arc [1]. The microstructure and ionic conductivity of LiPON films are significantly affected by the fraction of free lithium in the vapor flow, which is controlled by changing the frequency of interaction of electrons with evaporated particles. This paper presents the results of studying the conditions of anodic evaporation of Li_3PO_4 in an electron flow from a discharge plasma with a self-heating hollow cathode and the effect of free lithium in a vapor–gas mixture on the properties of deposited LiPON films.

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HYDROGEN SULFIDE PYROLYSIS BY THE MEANS OF HIGH VOLTAGE AC PLASMA. THERMODYNAMIC EVALUATION

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Hydrogen sulfide (H_2S) is produced as a byproduct of fossil fuel industry It is then processed at oil refinery facility into elemental sulfur and sulfuric acid. Due to its high hydrogen content, hydrogen sulfide could be used as a source of hydrogen gas.

Analysing the high temperature pyrolysis of hydrogen sulfide Its standart enthalpy of formation is -21 kJ/mol (-618kJ/kg), which is less than that of most other common hydrides.

One of the methods of heating hydrogen sulfide to high temperature is by using plasma arc[1,2]. For this, use of shielding gas is required for example, argon, to prevent sulfur from forming in the area near electrodes, as it can disrupt plasmatron's operational stability.

In this paper a preliminary thermodynamic estimation of plasma assisted hydrogen sulfide pyrolisys with a shieldig gas is presented.

The relation between reaction products of hydrogen sulfide-argon mixture (with ratio 1:1 by mass) pyrolysis and temperature was analysed. As seen on figure below, the hydrogen sulfide concentration drops as the temperature rises, reaching zero at 4000K, which well within capabilities of arc plasma torches.

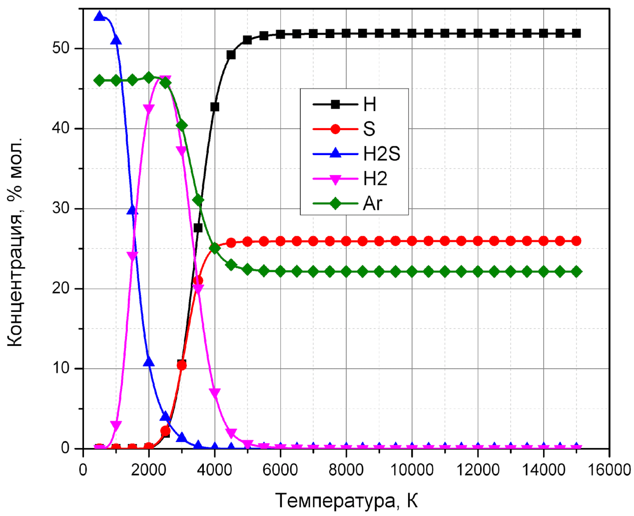

Figure – Relation between reaction products of hydrogen sulfide-argon mixture pyrolisis and temperature.

The decrease of content of all components but argon indicates that it's flow rate consistute little effect on the reaction products. For mass ratio $H_2S/Ar=1$ and temperature of 4000K the process energy numbers are: specific energy input – 12,9 MJ/kg plasmagenerating mixture (plasma enthalpy), 25,8 MJ/kg hydrogen sulfide, 439 MJ/kh hydrogen gas.

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DIAGNOSTICS AND APPLICATIONS OF DBD IN CONTACT WITH LIQUIDS

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Non-thermal plasmas generated in contact with liquids have been extensively investigated primarily due to the formation of reactive nitrogen species (RNS) and reactive oxygen species (ROS) in plasma treated liquids. Their existence in a liquid exposed to plasma allows a wide range of applications, particularly degradation of pollutants in water [1 – 7]. The generation of RNS and ROS in the considered liquid can be influenced by the reactor configuration, composition of the working gas and applied operating parameters. One of the realizations of non-thermal plasma above a liquid is water falling film dielectric barrier discharge (DBD) reactor in which DBD forms plasma above a thin film of falling water, see Fig. 1. To get a better insight into the plasma in the reactor and plasma-liquid interactions, distilled water was treated in different gas atmospheres: ambient air, nitrogen, oxygen, argon and helium. Electric parameters were monitored by a digital oscilloscope and a high voltage probe. Q-U graphs were used for determination of electric power dissipated in the plasma. The plasma characteristics were examined using spectroscopic methods in UV-Visible region using wide range spectrometer. The most challenging task in characterizing the plasma-water interactions is the measurement of radicals like •OH radical, due to its non-selective reactivity and short lifetime. Its quantification is of crucial importance since it non-selectively reacts with pollutant molecules and it is considered to be the key molecule in water purification processes, and also has great impact on biological systems. In this paper we report on the study of the long-living species formation and production of short-living hydroxyl radical whose quantification is based on trapping reaction with DMSO. Here, the parameters such as pH and conductivity and concentrations of hydrogen peroxide (H_2O_2), nitrite (NO_2^-), nitrate (NO_3^-) and hydroxyl radical (•OH) were measured.

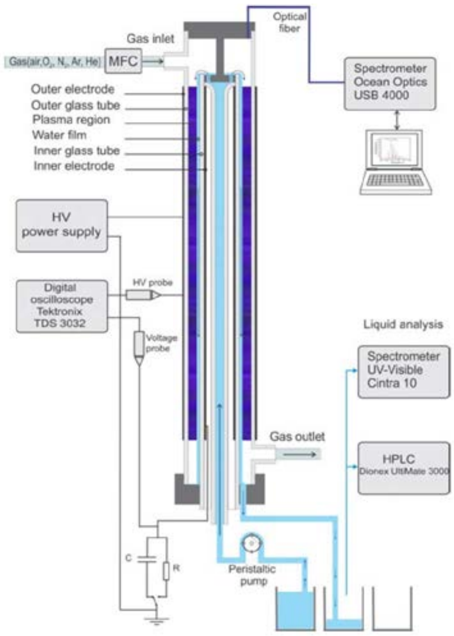

Fig.1. Schematic of the experimental set up.

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SYNTHESIS OF ZIRCONIUM DIBORIDE NANOPOWDERS BY INTERACTION OF ZIRCONIUM AND BORON IN AN ELECTRIC ARC DISCHARGE THERMAL PLASMA FLOW

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Zirconium diboride nanopowders are of interest for new composite materials design with increased heat resistance, which are in demand in the aerospace industry [1,2]. Significant attention has been paid to the development of new effective methods for obtaining metal borides, including zirconium boride, over the past decades [3,4]. Nanoscale materials with enhanced operational characteristics can be obtained using powder metallurgy methods with the use of nanopowders.

Plasma chemical synthesis is one of the promising methods for practical implementation of the synthesis of nanopowder materials, however, there is almost no information on research and developments in the field of obtaining ZrB_2 nanopowders by plasma chemical synthesis.

Experimental testing and investigation of plasma chemical synthesis processes of zirconium diboride nanopowders were carried out to determine the possibilities of controlling the properties of the powder obtained, the yield of the target product, and the process performance while maintaining high resource of technological equipment. Experimental work was carried out to investigate the plasma chemical synthesis process of zirconium diboride nanopowder by introducing boron and zirconium into an argon-hydrogen and nitrogen plasma in the form of a mixture of individual element powders.

As a result of the experiments, nanopowders (Fig. 1) with a specific surface area of 15–50 m^2/g were obtained, consisting mainly of zirconium borides, zirconium, and its oxides.

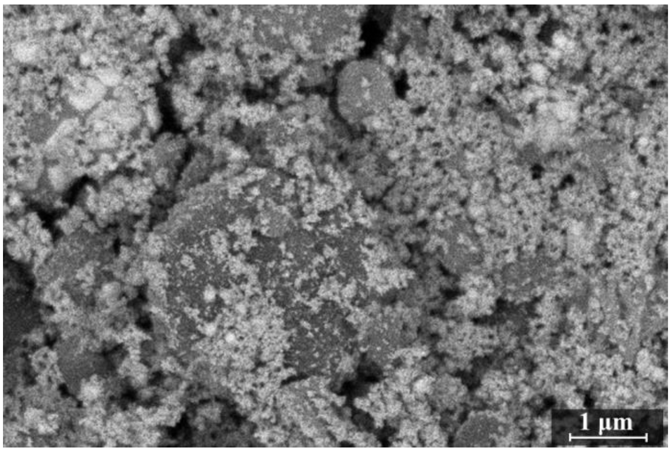

Fig. 1. SEM-image of obtained nanopowder.

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INFLUENCE OF MPC PLASMA TREATMENT ON THE PROPERTIES OF STEEL SURFACE WITH DEPOSITED TITANIUM - NITRIDE

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Magnetoplasma compressor (MPC) is a type of plasma accelerator with operation based on the common theory of dense plasma flow and acceleration developed by Morozov [1, 2]. The lifetime of the compressed plasma flow in MPC is around 150 µs, electron density and temperature are of the order of 10^{22} m^{-3} and 1 eV, respectively [3].

The goal of the present study is to investigate how high thermal loads produced by plasma change the structure of the treated surface after one, two or three plasma shots. The energy flux density of the plasma flow in the plasma-sample interaction area is 10 J/cm^2 [4].

Steel samples (100Cr6) with a deposited 800 nm thick layer of titanium nitride, are treated with a plasma formed within a MPC device. Titanium–nitride films were deposited by a direct current (DC) reactive ion sputtering system (Balzers).

Figure 1 shows a diagram of the setup for carrying out the experiment. The capacitor battery is charged to the operating voltage 4 kV from a DC source and the total amount of energy stored in the capacitor bank is 6.4 kJ. By bringing the trigger signal to the ignitron, it is discharged through the MPC electrode system. Helium - hydrogen mixture (p=10 mbar) is used as a working gas in vacuum chamber.

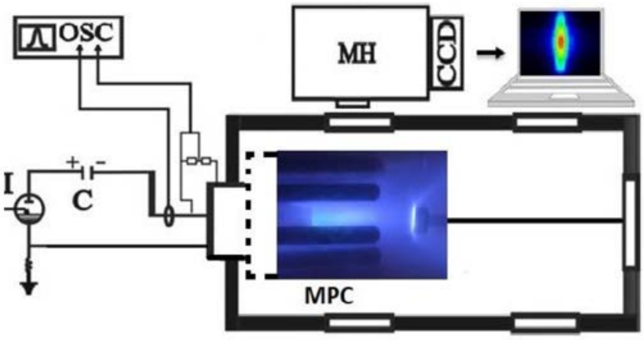

Fig.1. Experimental setup.

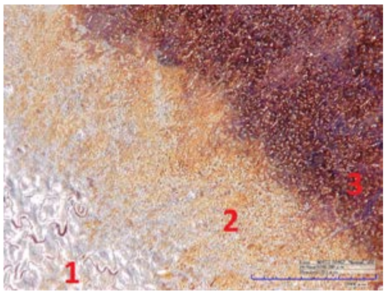

Fig.2. Optical microscope image of the sample after one plasma treatment (50 x magnification).

During plasma treatment melting, mixing, and alloying occur and, after the recrystallization process, the chemical and physical characteristics of the surface are changed. Significant improvement of material hardness was achieved. From the initial 200 HV, the hardness of treated steel samples goes up to 430 HV after three plasma treatments. For the sake of comparison, when steel 100Cr6 without deposited TiN alloy is treated with plasma, the achieved hardness value, after three plasma treatments, was 325 HV [5].

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SURFACE ALLOYING OF HYPEREUTECTIC SILUMIN WITH TITANIUM TO IMPROVE STRENGTH AND PLASTIC CHARACTERISTICS

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Silumin is an alloy of aluminum and silicon. Hypereutectic silumin contains over 12 wt.% silicon, which ensures its higher hardness and increased prospects for use in mechanical engineering and instrumentation (for example, for the manufacture of parts for internal combustion engines or miniature bearings). Silumins are a cheap alloy, have good corrosion resistance and good casting properties, low specific gravity [1-3].

The aim of the work was to identify methods and approaches to significantly improve the microhardness, tribological characteristics, strength and plasticity of hypereutectic silumin by its surface alloying. Alloying was carried out using a vacuum-arc deposition of a titanium film and its subsequent fusing with a pulsed electron beam during the 1st and 3rd exposure cycles in a single vacuum space at the "COMPLEX" setup. The research material was silumin of hypereutectic composition (Al-23Si).

Scanning electron microscopy was used to study the structure and elemental composition of the surface formed as a result of high-speed cooling of the "Ti film / (silumin) substrate" system treated with a pulsed electron beam at 1 and 3 exposure cycles. It has been established that in mode 10 (1) and 10 (3) there is no melting of the titanium film, in mode 25 (1) there is partial melting and destruction of the titanium film, in mode 25 (3) intensive melting occurs surface layer with the formation of a structure of high-speed cellular crystallization.

Mechanical tests of modified silumin samples were carried out. Hardness was determined by micro-indentation method. Electron-beam processing of the "film (Ti) / (silumin) substrate" system leads to an increase in the hardness of the material by ~3.0 times. Tribological tests revealed an increase in the wear resistance of silumin by ~3.0 times and a less significant (1.25 times) decrease in the friction coefficient.

The work was carried out within the framework of the state task of the Ministry of Science and Higher Education of the Russian Federation № FWRM-2021-0006.

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ENHANCEMENT OF PHOTOCHROMIC PROPERTIES OF MOO$_3$ AND WO$_3$ BY PLASMA TREATMENT OF SOLS

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Transition metal oxides (MoO_3, TiO_2, V_2O_5, WO_3) have photochromic properties due to the reversible $Me^{n+} \rightarrow Me^{(n-1)+}$ transition. The photochromism phenomenon manifests itself when certain conditions are reached, such as particle size (less than 20 nm), structure, and phase composition. The enhancement of the photochromic effect is essential for the development of smart materials. This can be achieved by changing the structure, particle sizes (transition to quantum dots) and creating doped structures or composites based on double/ternary oxides [1]. The synthesis method largely determines the structure and properties of the resulting materials. It was previously established that plasma in contact with a liquid is a promising tool for obtaining pure oxide structures [2]. The resulting structures have a high degree of crystallinity. It is significantly reduces the photochromic properties of materials. In addition, a new doping method using plasma has been successfully introduced [3].

Sols of tungsten and molybdenum (VI) oxides stabilized with polyvinylpyrrolidone (PVP) with different molecular weights (10,000, 55,000, and 1,300,000) were treated with AC underwater diaphragm discharge plasma. The processing time was 60 s. The morphology of the resulting particles was examined using a transmission electron microscope (FEI Osiris). Treated and untreated sols were irradiated with UV light with a lamp (NU-6 KL 6 W) for 30 min. The dynamics of colorationstaining and discoloration was recorded spectrophotometrically (SF 56).

The TEM data showed that the action of plasma on a PVP 10000 sol leads to the formation of a polyhedral structure with a crystallite size of 4-6 nm. In the ash with PVP 55000, fractal structures are formed (crystallite size of 2-3 nm). In the case of sols with PVP 1300000, the action of plasma leads to the formation of binary structures based on MoO_3/WO_3 (crystallite size of 12-18 nm). Studies of photochromic properties have shown that the sols after plasma treatment have a higher degree of coloration (upto 30-35%). The discoloration of sols after plasma treatment increases by 3.5-7 times, depending on the molecular weight of the stabilizer. The untreated sols irreversibly transform into the colored state after 5 (in the case of WO_3) and 3 (in the case of MoO_3) cycles, while plasma treatment makes it possible to increase the number of cycles by a factor of 2–2.5.

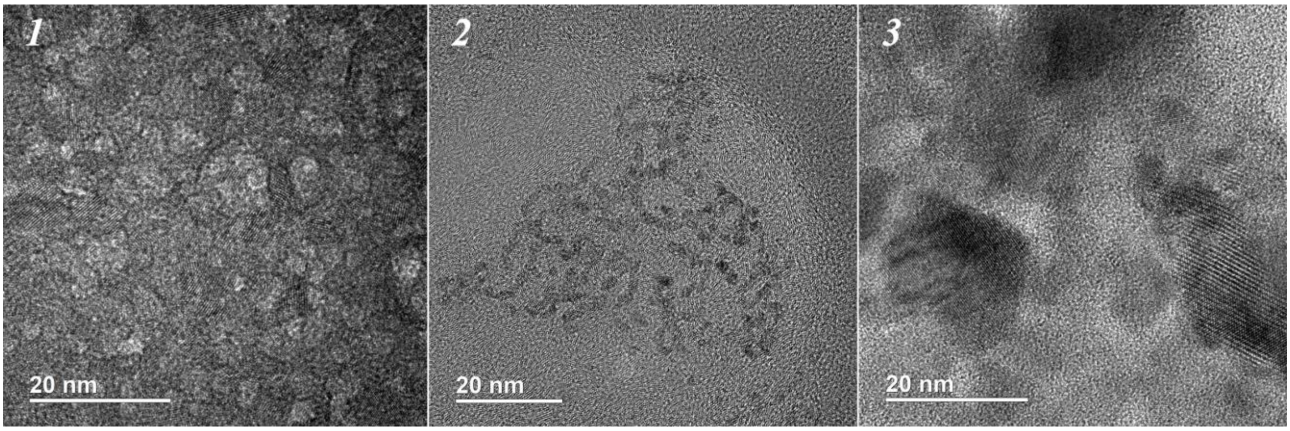

Fig.1. The TEM images of sols for example MoO_3 stabilized by PVPwith different molecular weight 10,000 (1), 55,000 (2), and 1,300,000 (3).

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RESEARCH OF PHYSICAL AND MECHANICAL PROPERTIES OF POLYETHYLENE FILMS MODIFIED BY AN ELECTRON BEAM IN THE ATMOSPHERE

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Composite materials based on polymer films are increasingly used in industry [1]. In particular, it can be noted the need to create sticky tapes that are used to insulate pipelines [2]. One of the technical features of polymers is low hydrophilicity, which leads to the need to take additional measures to increase it in order to improve the adhesive properties of the surface.

The use of new composite materials, among other things, is due to the development and use of new methods and approaches, and in particular, the development and creation of new equipment for modifying the surface of polymers that meets industrial requirements (not only in terms of processing quality, but also in terms of productivity). For example, low-energy electron accelerators can be used to create them, allowing the generation of large-section electron beams with their output into the atmosphere.

The purpose of this work was to determine the fundamental possibility of modifying polyethylene films by an electron beam of large cross-section at atmospheric pressure. The modification was carried out on an upgraded pulsed wide-aperture electron accelerator "DUET" with a grid plasma cathode and the output of the generated beam of large cross-section (15×75 cm^2) into the atmosphere [3]. The schematic diagram of the accelerator is shown in Figure 1.

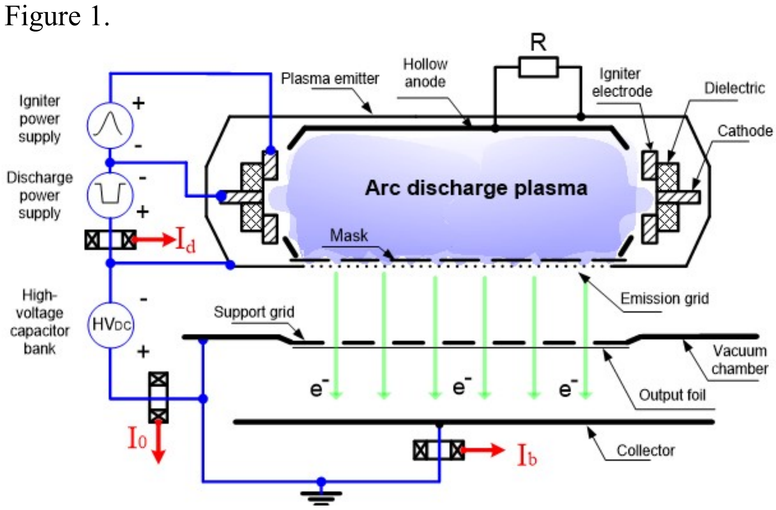

Fig.1. Electron accelerator with grid plasma emitter: 1 – plasma cathode; 2 – cathode; 3 – igniter electrode; 4 – emission grid; 5 – mask; 6 – hollow anode; 7 – support grid; 8 – output foil; 9 discharge power supply; 10 – igniter power supply; 11 – high-voltage capacitor bank; 12 - collector.

Modification of polyethylene films with a thickness of 150 microns was carried out at an accelerating voltage of 160 kV, a beam current density of 9 mA/cm^2, a pulse duration of 100 mcs and a pulse repetition frequency of 2 s^{-1}. The processing modes differed in the number of pulses: 100, 500 and 1000. At various radiation intervals, the study was carried out: the edge angle of wetting by the “lying drop” method; chemical structure by infrared spectroscopy; qualitative and quantitative composition by scanning electron microscopy; morphological properties by atomic force microscopy and mechanical properties – values of elongation and maximum load. It is shown that modification of polymer films by an electron beam in the atmosphere can change their structural-morphological and physico-chemical properties, and, as a result, improve the adhesive properties, which opens up new technological possibilities for equipment of this class.

The work was supported by the grant of Russian Science Foundation (Project No 20-79-10015-P).

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GENERATION OF GAS-METAL BEAM-PLASMA FORMATIONS IN A NON-SELF-SUSTAINED GLOW DISCHARGE

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In the modern world, a vacuum arc is most often used to depositing coatings in plasma technologies [1]. This method is called physical vapor deposition and is the most attractive of the variety of coating options.

In the traditional scheme two electric arc evaporators were used to generate metal plasma, as well as a PINK gas plasma source. The anode for the plasma sources was the inner walls of a vacuum chamber. The gas plasma source formed a plasma with a concentration gradient directed towards the walls of the chamber, while the maximum concentration area was located near the outlet of the source [2].

In the second discharge scheme [3] a gas-metal beam-plasma formation was formed in the hollow cathode of non-self-sustained glow discharge. A non-self-sustained glow discharge was ignited between the walls of the vacuum chamber, which are the cathode, and the annular anodes located opposite the output aperture of the arc evaporators, which are also the anode for arc discharges.

In both discharge circuits, a (Zn+Ti-B-Si-Ni)N coating was deposited. The microhardness of the coatings was measured on a KBW-1 instrument (KB Pruftechnik GmbH, Germany) using a Vickers diamond pyramid at an indenter load of 0.1 N (10 g). According to the results of measurements, the hardness values were 41 GPa during deposition in the traditional scheme and 47.8 GPa during deposition in the scheme in a gas-metal beam-plasma formation.

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G3-P-000201

STRUCTURAL CHANGES IN THE MAGNETITE SURFACE UNDER THE INFLUENCE OF A DIELECTRIC BARRIER DISCHARGE AND HIGH-POWER ELECTROMAGNETIC PULSES*

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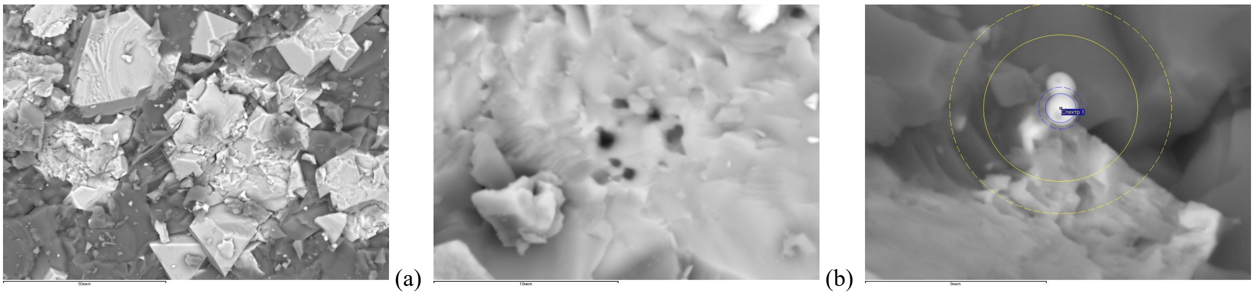
At present, the problem of increasing the efficiency of the enrichment of iron ore and the quality of magnetite concentrates is very relevant. Magnetite (Fe_3O_4; $FeO{\cdot}Fe_2O_3$) is a magnetic iron oxide and natural oxide geomaterial. The mechanism of structural-phase transformations of magnetite under the influence of microwave fields attracts special attention in connection with the development of technologies for changing the phase composition, surface and magnetic properties of the mineral in order to increase the efficiency of enrichment of magnetite ores. In this research we present the new experimental results on the morphology changes and structural surface transformations of the magnetite from Mikhailovsky deposit under the influence of dielectric barrier discharge (DBD) in air and high-power nanosecond electromagnetic pulses (HPEMP). Magnetite characterized by the following chemical composition (XRF), wt %: 61.2 Fe, 11.4 MgO, 5.2 Al_2O_3, 2.4 SiO_2, 1.4 CaO, 0.5 MnO, 0.5 TiO_2, 0.2 S. Mineral presented in the form of isometric crystals of octahedral and rhombododecahedral habit, having well-formed faces in the initial state (Fig. 1a).

Electrode voltage in the cell of the barrier discharge generator (DBD) was 20 kV; pulse duration was ~10 μs; duration of a pulse leading edge was ~300 ns; rate of pulse repetition was 15 kHz; length of interelectrode gap was ~5 mm. With the HPEMP effect, the duration of high-voltage pulses was 4–10 ns, pulse amplitude was U_A~25–30 kV, strength of the electric field in the 5 mm interelectrode gap, $E \sim 10^7$ $V{\times}m^{-1}$; rate of nanosecond pulse repetition was f=100 Hz. The duration of sample treatment varied in the range of $t_{treat.}$=10–100 s. The morphology and elementary composition of micro- and nanoformations on the magnetite surface have been investigated using methods of analytical electron microscopy (SEM–EDX).

Under DBD conditions, the surface of mineral particles located in the space between the dielectric barrier and one of the electrodes of the discharge cell was exposed to a strong electric field, ion wind, high concentration of chemically active particles (O_3, O_2, H_2O_2, OH), and an elevated temperature of the dielectric barrier. As a result of exposure to DBD ($t_{treat.}$=50–100 s), we have observed the damage of the flat faces and perfect edges, destruction of crystal tops, formation of the detrital (clastic) particles, discharge current channels (Fig. 1b), the extended tortuous trans- and intercrystalline microcracks propagation on the magnetite particles surface. During the exposure to HPEMP, the air gap (~0.1–0.5 mm in size) between the mineral particles surface and the active electrode of the pulse generator remained, which led to the development of the numerous spark microdischarges between the particles surface and electrode. Structural changes in the magnetite surface under the influence of HPEMP ($t_{treat.}$=30–50 s) are associated with the formation of amorphous microphases of iron oxides and/or hydroxides of complex sintering shape. At $t_{treat.}$=50–100 s, we observed the separation of spherical microparticles ~1−10 μm in size (Fig. 1c); these particles, apparently, belong to the amorphous phases of iron oxides and/or hydroxides with impurities of oxides of Si, Mg, and Ca. Advantages are shown of using brief energy (DBD and HPEMP) treatments ($t_{treat.}$=30–50 s) to modify the chemical structure of magnetite surface and its technological properties. Preliminary DBD treatment allowed to improve the quality of the magnetite concentrate by increasing the extraction of the rock-forming mineral (quartz) into the froth product of flotation.



(a) (b) (c)

Fig.1. Micrographs of magnetite surface: (a) before and (b, c) after exposure by (b) dielectric barrier discharge and (c) high-power nanosecond electromagnetic pulses ($t_{treat.}$=50–100 s); SEM, the scales are (a) 50, (b), (c) 10 μm.

* The work was partially supported by the President of the Russian Federation under contract number NSh–7608.2016.5 (academician V.A. Chanturiya's Scientific School).

EFFECT OF LOW-TEMPERATURE PLASMA GLOW DISCHARGE ON PHYSICOCHEMICAL PROPERTIES OF POLYLACTIC ACID SURFACE

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Currently, more and more works are aimed at creating materials that are as close as possible to the skin in terms of properties and structure. The variety of created wound coverings is explained by the large number of used polymers. The most suitable biodegradable material for medical applications is polylactic acid (PLA) since its degradation products are nontoxic to the human body. However, the disadvantages of PLA-based materials include the low wettability of the surface, as well as the absence of nitrogen-containing functional groups in its surface layer, which ensure the most efficient colonization and growth of the human cell population [1]. To graft amino groups onto the surface of PLA-based scaffold a low-temperature glow discharge plasma is used, maintained in a flow of plasma-forming gas - argon and diethylamine vapor (DEA). The mass flow rate of argon is 230 mg/min, DEA is 2 mg/min (corresponding to 1 wt.% DEA in the plasma). The discharge burning voltage in argon is 380 ± 10 V; in the case of injection of diethylamine, it is 410 ± 10 eV. The average discharge current is set to 40 mA, the discharge power is 20 W. The duration of plasma treatment of materials is 5 minutes.

Irradiation of PLA-based materials by low-temperature plasma flows leads alterations in their chemical composition. Surwey spectra reveal the presence of the main PLA elements carbon and oxygen, but a new peak with binding energy ~399.9 eV, corresponding to atomic nitrogen (7.86 at.%), appears following Ar/DEA plasma treatment. The content of the carbon bonds in the coordinations -O-CH- and O-C=O decreases after plasma treatment. This phenomenon may be associated with the processes of decarbonylation and decarboxylation in macromolecules. The content of the carbon bonds in the coordination CH_3-CH- is shown to increase after plasma treatment. The maximum content of CH_3-CH- equal to 44.44 at.% is observed when the PLA surface is treated with the Ar/DEA plasma. According to the C1s spectra, treatment of the PLA surface with glow discharge Ar/DEA plasma results in the destruction of the polymer chains accompanied by the -C-N bond formation with the binding energy of 286.4 eV (25 at.%).

PLA is known for its high hydrophobicity, which can be altered by plasma technology. The initial PLA materials contact angles are 123.3° with water and 142.5° with glycerol. It was found that the contact angle both with water and glycerol indicates wettability improvement after plasma treatment. It was found that the contact angles both with water and glycerol decreased, that indicates the wettability improvement after plasma treatment. The minimum water contact angle ($\theta = 56.3°$) and the minimum glycerol contact angle ($\theta = 66.2°$) is found for the Ar/DEA plasma-modified PLA samples. Surface wettability improvement is due to the formation of hydrophilic functional groups (-C-N) in the plasma-modified material.

To sum up, Ar/DEA flow glow discharge plasma treatment is an effective technique for surface physicochemical property modification of PLA based materials.

This work was supported by the Tomsk State University Development Program (Priority-2030).

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G3-P-001301

MATTER DENSITY DISTRIBUTION OF COPPER CYLINDRICAL CONDUCTORS AT SKIN EXPLOSION

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Plasma formation on the surface of a conductor is a key problem in terms of the energy deposited in a metallic substance. The experiments were carried out on MIG generator (current amplitude up to 2.5 MA, current rise time 100 ns). The internal structure of the near-surface plasma, the estimate of the density of matter in it, and its radial distribution were studied using X-ray radiography based on the X-pinch. The distribution profile of a substance along its radius at different points in time was modeled using the developed calculation program using the Abel transform. Dependences of $\mu \cdot \rho$ on the radius of a copper conductor are obtained in a selected section of the X-ray diffraction pattern of its explosion. The value of the mass radiation absorption coefficient μ was determined from the X-ray transmission patterns of stepped filters made of the same conductive material as the exploding one. The density of the ρ conductor substance was estimated at various times from the beginning of the current.

G3-P-001602

THE EFFECT OF LOW-INTENSITY e-BEAM AND UV EXPOSURE ON DISSOLVED TOXIC COMPOUNDS

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In the world, on the one hand, there is an intensive use of the electron beam in various areas of technological production: processing in the synthesis of polycarbonate for the production of organic electronic devices; study of photoconductivity during electron bombardment; production of sensitive and inexpensive capacitive sensors; micronanofluidics and many others. However, the mechanism of action of an electron beam of different intensity on dissolved organic compounds has not yet been fully studied. On the other hand, wastes that usually contain substituted phenols, various organic compounds that harm the life of biological organisms get into natural waters. Water pollution by toxic persistent compounds of chemical enterprises is a serious concern all over the world. Traditional wastewater pre-treatment technologies such as adsorption, coagulation, biochemical, electrochemical and enzymatic oxidation are often ineffective or include partial degradation of dissolved toxic compounds with the formation of secondary pollutants. As a rule, schemes based on ubiquitous biodegradation do not provide the degree of removal of all types of pollutants necessary for the organization of wastewater reuse. In the world community, the issue of developing effective and fast technologies for removing toxic organic compounds from the environment is acute. It is believed that it will be possible to cope with these problems only as a result of the large-scale application of new promising modern purification technologies.

Studies on the decomposition of impurities of various small molecules in air under the action of a pulsed electron beam showed that the energy consumption of the electron beam for the decomposition of these molecules is one of the lowest (20–30 eV for breaking one molecular bond). This is due to the fact that when exposed to an electron beam with the environment, reactive particles are actively generated - free radicals, ions or excited molecules, which means that conditions are created that are favorable for the occurrence of chain processes.

The general physical principle of the transformation of dissolved organic molecules under the action of UV radiation is that after the absorption of a light quantum, the molecule goes into an excited state. This process takes a long time and is quite energy intensive. Pulsed electron beams are capable of penetrating deeper layers than UV radiation. The depth of penetration of the electron beam depends on the energy of the beam and the nature of the irradiated substance. The study of the cathodoluminescence of solutions of dissolved organic compounds under the action of an electron beam contributes to solving the problem of diagnostics and utilization of toxic substances in order to reduce the burden on the environment and the content of transformation products. The main goal of our study is to study the decomposition of organic compounds (phenols, dyes, antibiotics and humic acids) during and after exposure to a pulsed electron beam by optical absorption and luminescence spectroscopy. The report will include a detailed analysis of the loss of compounds in water, the formation of secondary products under the action of an e-beam with parameters [1]; comparison with data on UV irradiation by excilamps with different wavelengths of radiation. Transformation was diagnosed using cathodoluminescence and electron absorption spectroscopy.

This work was performed within the framework of the State Assignment of the Ministry of Education and Science of the Russian Federation (Project No. AAAA-A19-119020790031-5).

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THE INFLUENCE OF SUBSTRATE EXPOSURE MODES ON THE PROPERTIES OF CHROMIUM COATINGS DEPOSITED VIA MAGNETRON SPUTTERING

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During magnetron sputtering deposition many factors are present which could potentially influence the properties of coatings [1]. One of these factors is the position of the substrate relative to the magnetron target. The relative location of a substrate regarding a magnetron target determines the incident angle of the flux and the deposition rate, and it can change over time during deposition process. For instance, the deposition for research purposes can be performed onto nonmoving substrate, while in industrial applications, the rotational motion of substrates is used to obtain coatings with uniform structure [2]. An important issue to address is how the changes in the flux parameters, such as flux density, mean angle of incidence, kinetic energy of the atoms, etc., caused by the substrate position variation affect the resulting coatings and their properties.

The present study investigates this issue. To do this, the series of experiments was carried out. In the first set of experiments the substrate was placed at different distances related to the magnetron target. In the second one, the angle of orientation was the varying parameter. The third set of experiments was aimed at examining two types of rotational motion which involved just the axial rotation and the “planetary” rotation of the substrate.

In the figure 1, the setup of the axial motion experiment is shown with the representation of main varying characteristics.

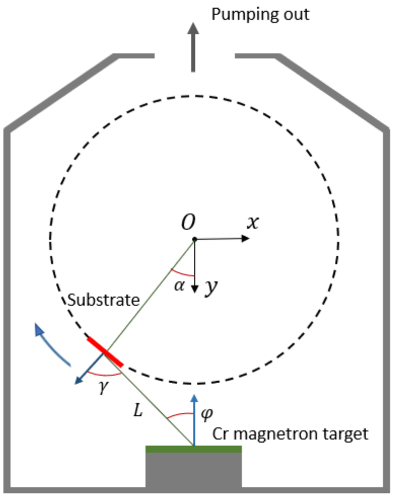

Fig.1. Experimental installation. L – the distance between the centers of a magnetron target and the substrate, γ – the angle between the flux and the substrate, φ – the angle between the flux and the target.

The properties of the coatings, including hardness, phase composition, and roughness were characterized using various analytical techniques such as X-ray diffraction, scanning electron microscopy, profilometry and indentation hardness tests.

In addition to that, a mathematical model was created to calculate the deposition rate and the thickness of the coatings obtained in a dynamic system. This allows to simulate the deposition process in different substrate exposure modes and to tie together the changes in the flux parameters with the properties of the coatings.

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NUMERICAL MODEL OF A UNIT GAP OF LTD SWITCH

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Gas switch is one of main component of the pulse power generator. Mean value and jitter of close time of the LTD switch is importance for proper operation of LTD generator. At present day several research aim to optimize of the triggering system of LTD cavity which need test both by calculate and by experimental study. However, used numerical model of the switch has constant close time. The study is aiming numerical model of the gap of the LTD switch with evaluate close time.

As a model, it is proposed to use the integral breakdown criterion describing the breakdown of a gap using sub microsecond trigger pulse [1]. The integral breakdown criterion assumes that the volt-second integral of the voltage above the static breakdown voltage (filled area in Fig.1) is a constant. In this case close time of a gap depends on rise rate of voltage.

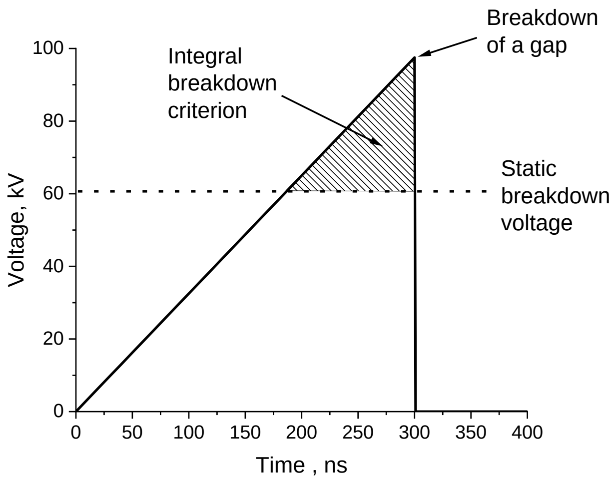

Fig 1. Voltage on a gap.

In [1] the gap has uniform electric field, filled with nitrogen at a pressure of 1 to 4 atm, and has a gap length of 5 to 20 mm. A gap of LTD switch has length 6 mm and filled dry air with pressure of 3.5 to 4 atm. Those conditions are close to the boundary ones, and it is necessary to check the applicability of the integral breakdown criterion for modeling of a gap of the LTD switch.

In this study, both a theoretical and an experimental verification were carried out of applicability assessment of the integral breakdown criterion. During the experiment, both the static breakdown voltage and the breakdown upon of a sub microsecond pulse were studied.

The results of the work performed showed the possibility of using an integral criterion for calculating the moment of breakdown of a single gap of an LTD spark gap. The value of the integral criterion and jitter of the moment of breakdown of the gap were calculated.

The work was carried out within the framework of the state assignment of the Ministry of Science and Higher Education of the Russian Federation on the topic No. FWRM-2021-0001.

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COMPLEX ELECTRON-ION-PLASMA TREATMENT OF SILUMIN*

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The paper presents the studies aimed at detecting the effect of the complex electron-ion-plasma modification on the properties, composition and structure of silumin of eutectic composition. Regularities of surface layer modification under electron beam effect in different irradiation modes on the system "nitride coating (0.25-2.0 μm)/silumin substrate" are obtained.

All silumin samples in the first stage were subjected to electron-beam with to remove contaminants and the pores of the original silumin structure. Then, a binary TiN nitride coating with high wear resistance, hardness and adhesion strength to silumin was deposited to the prepared substrates. Deposition was carried out from the plasma of low-pressure arc discharges by vacuum-arc plasma-assisted method at the "QUINTA" vacuum ion-plasma setup. Technical titanium (grade 2) was used as the material of the evaporated cathode. The growth rate of the TiN coating was 10.8 μm/h. Four coating thicknesses were chosen: 0.25; 0,5; 1.0 and 2.0 μm. The third stage of processing was electron beam irradiation at different parameters (pulse duration, number of pulses, energy density). The main studies of the TiN coating/silumin substrate system after electron-beam treatment were carried out at a TiN coating thickness of 1±0,1 μm.

Based on the results obtained using modern materials science methods, the following conclusions were made:

1. It has been found that for electron beam irradiation leading to an increase in mechanical and tribological characteristics of the nitride coating/silumin substrate system, it is necessary to irradiate the electron beam with a submillisecond duration at an energy density in the range of 5-15 J/cm^2. A range of 20-30 J/cm^2 can be used to form a surface alloy without retaining the phases of the initial nitride coating.

2. It has been found that in the selected coating/substrate system, a short-term energy input (≤50 μs) is undesirable, and a pulse duration of 100-200 μs is preferred. In this case, the nitride coating is not broken and the roughness is not increased. A high-adhesion wear-resistant system with a thickness of ~ 10 μm is formed.

3. It has been shown that the number of electron beam pulses on the nitride coating/silumin substrate system has practically no effect on the phase composition and structure, mechanical and tribological properties in the range of 1-15 pulses at a relatively low energy density (up to 15 J/cm^2).

4. It was found that in the case of nitride coatings, as a stage of complex electron-ion-plasma treatment of silumin of eutectic composition, it is more efficient to use a coating thickness of 0.5-2 μm to obtain a hard (HV≥2,2 GPa), wear-resistant (~10^{-4} mm^{3}N^{-1}m^{-1}) and a high adhesion (L > 2.5 N) surface layer of the nitride coating/silumin substrate system.

5. It has been found that the optimal modes recommended for obtaining a surface layer of the TiN coating/silumin substrate system without or with insignificant destruction of the phases of the initial nitride coating, with relatively high hardness, wear resistance, adhesion strength, low roughness and friction coefficient can be considered as follows: τ=200 μs, N = 15, E_s = 15 J/cm^2; τ=100 μs, N = 5, E_s = 15 J/cm^2; τ=50 μs, N = 5, E_s = 5 J/cm^2.

* The work was supported by the Ministry of Science and Higher Education of the Russian Federation under project FWRM-2021-0006.

COMPUTER SIMULATION OF THERMAL FIELDS OF THE CR-MO-ZR SYSTEM FOR COATING FORMATION USING A LOW-ENERGY HIGH-CURRENT ELECTRON BEAM

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Currently an important task is to achieve a more accident tolerant fuel (ATF) cladding that by virtue of its higher oxidation resistance would allow for increased coping times under a loss of coolant accident (LOCA) scenario [1]. One of the many ways to create ATF is to apply Cr-containing coatings using a low-energy high-current electron beam [2, 3]. Mo is used as a barrier layer between Zr and Cr-containing coatings [4]. For example, the FeCrAl alloy provides excellent oxidation resistance, but Fe forms eutectics with Zr at temperatures up to 928 °C, which leads to mutual diffusion and associated melting. Mo is used as an interlayer coating due to its high melting point (2893 °C), low diffusion rate of Cr, Fe and Zr into Mo, and high eutectic points with Fe and Zr [5-7].

The temperature fields for the three-layer system Cr (film)-Mo (film)-Zr (substrate) have been calculated. The dependences of the melting thresholds of Cr, Mo, and Zr for the Cr-Mo-Zr system depending on the thickness of the Cr film were calculated. It was found that during irradiation of the Cr-Mo-Zr system with a low-energy electron beam, the surface Cr film begins to melt first. Then the Zr substrate material begins to melt. The refractory material of the Mo barrier film melts last. Therefore, the melting threshold of the Cr-Mo-Zr system, when the melt of all elements of the system exists, should be taken as the melting threshold of Mo, and the melting thickness of Zr should be taken as the thickness of the melt. It was found that the thickness of the Cr film greatly affects the melting thresholds of each element of the system. Thus, for a system with a Cr film thickness of 1 μm and Mo film thickness of 1 μm, the melting thresholds for the Cr film is 3.1 J/cm^2, for the Zr substrate is 3.7 J/cm^2, and for the melting of the Mo barrier film is 5.8 J/cm^2, which is the minimum LEHCEB energy density for melting the system in question. For the system with Cr film thickness equal to 2 μm, Mo film thickness equal to 1 μm, the melting threshold for Cr film is 3.7 J/cm^2, for Zr substrate - 4.9 J/cm^2, and for Mo barrier film melting - 7.7 J/cm^2. For the system with a 3 μm Cr film thickness and a 1 μm Mo film thickness, the melting thresholds are 4.2 J/cm^2 for the Cr film, 6.2 J/cm^2 for the Zr substrate, and 9.7 J/cm^2 for the Mo barrier film melting.

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INVESTIGATION OF THE CONDITIONS FOR OBTAINING NANOCOMPOSITE SIALCN COATINGS BY ANODIC EVAPORATION OF AL AND DECOMPOSITION OF AN ORGANOSILICON PRECURSOR IN A DISCHARGE WITH A SELF-HEATING HOLLOW CATHODE.

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The plasma composition in the medium Ar+N2+Al+hexamethyldisilazane (HMDS) was studied by optical emission spectroscopy. The effect of aluminum vapors on the degree of decomposition of hexamethyldisilazane is investigated, and the results of the study of the effect of the current of the main discharge gap and the current in the crucible circuit on the composition and degree of activation of the vapor-gas mixture are presented. As a result, SiAlCN test coatings were obtained by anodic evaporation of aluminum and decomposition of an organosilicon precursor in a discharge with a self-heating hollow cathode.

The scheme of the experimental setup is shown in Fig. 1 and described in detail in [1]. The arc discharge is used to ionize gases and decompose hexamethyldisilazane vapors, as well as to heat the crucible and vaporize aluminum using two independent anode sections (cooled hollow anode, uncooled anode crucible).

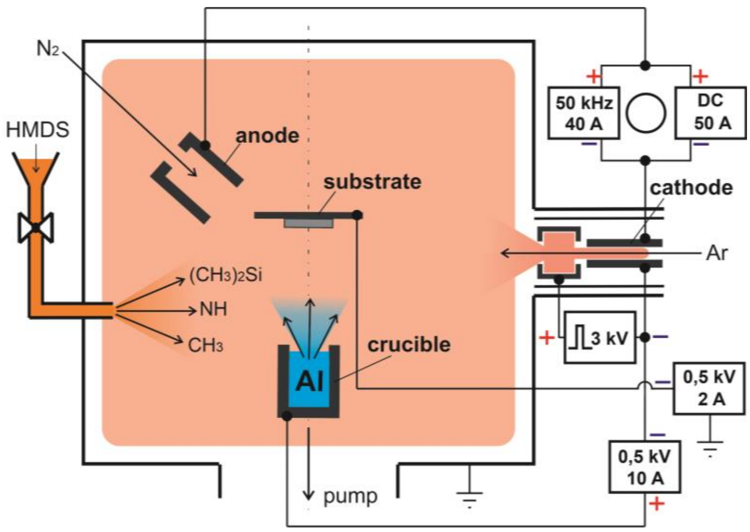

Fig.1. Electrode scheme of experimental facility.

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INFLUENCE OF ALUMINUM SUBSTRATES ON MECHANICAL PROPERTIES OF COATINGS PRODUCED BY MICROPLASMA OXIDATION

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One of the promising materials for many industries is aluminum and its alloys. Aluminum has a low weight relative to steel and cast iron, high electrical and thermal conductivity, and is easy to process. The disadvantages of aluminum products include relatively low hardness and wear resistance, uneven oxide film. Processing by microplasma discharges in an electrolyte medium makes it possible to form protective oxide coatings that increase wear resistance, hardness, and corrosion resistance [1].

The method of microarc oxidation (MAO) consists in processing the product with microplasma discharges in an electrolyte medium and forming a protective coating at the metal-electrolyte interface consisting of oxide forms of the substrate metal and electrolyte elements. Coatings obtained by the MAO method have high values of hardness, corrosion resistance, and wear resistance [2, 3, 4].

The study of the influence of aluminum alloy substrates on the mechanical properties of coatings obtained by the MAO method will make it possible to better predict the properties of coatings.

MAO coatings were formed in the anodic mode according to the MANEL technology on samples (ø50 mm and h=2 mm) of aluminum alloys D16, AMg2 in Manel-B electrolyte (pH=6) using an AGL-ARCCOR III switching power supply (EleSy company) at voltage up to 600 V, pulse duration 200 µs, frequency from 70 to 150 Hz. As part of the work, 2 technological modes were implemented and 3 samples were obtained for each.

At the beginning of the MAO process, a transition layer up to 20 µm was formed on the samples, and then the coating thickness increased to 40 µm. The average rate of coating formation was from 1 to 10 µm/min; after coating, the samples were washed in distilled water and dried in an oven at a temperature of 100 ± 5 °C.

The microhardness was measured according to ISO 14577-1 on an ultramicrohardness tester DUH 211S (Shimadzu, Japan) by indentation of a Berkovich trihedral diamond tip (pyramid with an angle of inclination of the faces 115°) under the required load with determination of the indentation hardness values Hit and HMT115, automatically fixed by the device according to the value of the indentation depth, nominal Vickers hardness HV, recalculated from the Hit values, as well as direct measurement of the dimensions of indentation marks to determine the microhardness value "Triangular pyramid hardness with 115° tip angle". In the process of measuring microhardness, the device also recorded the values of the elastic modulus, the coating thickness was controlled by a Positector 6000 eddy current thickness gauge.

The paper presents the distribution of elements in aluminum substrates before and after microplasma oxidation. Comparison of the mechanical properties of coatings obtained on substrates from different aluminum alloys. Influence of technological modes of formation of MAO coatings on their properties.

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HYDROGEN TREATMENT OF SINGLE-WALLED CARBON NANOTUBES IN INDUCTION-COUPLED PLASMA DISCHARGE

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Nowadays, a lot of attention is paid to new materials, in particular synthesis and use. Graphene and carbon nanotubes are among such actively studied substances. These materials have unique electronic properties, but on the other hand they are quite strong and inert [1]. The creation of special conditions, for example, in the presence of a plasma discharge, makes it possible to modify these carbon nanomaterials [1, 2]. These materials have different properties compared to the original substance. For example, hydrogenation of graphene with the help of various methods leads to the appearing of a band gap [3, 4], and as a result of this, the electronic properties change. Modified carbon nanostructures are proposed to be used, for example, as transistors or sensors [4].

One of the most effective and promising ways to modify carbon nanostructures is the use of plasma discharge. The advantage of plasma hydrogenation of carbon nanostructures is the ability to easily adjust the processing parameters. The second advantage is that the induction-coupled plasma discharge weakly pollutes the sample, which has a positive effect on the final "purity" of the experimental products. The disadvantages of this method of treatment are the relative complexity and high cost of the necessary equipment.

During the hydrogenation of single-walled carbon nanotubes, samples were deposited on a stainless steel or glass substrates. Next, the samples were placed in a chamber at a distance of 30 cm from the place of formation of a plasma discharge with a power of 50 W. The pressure in the chamber was maintained at 55...60 mTorr. In the course of the work carried out, several experiments were carried out in order to isolate the influence of various factors on the hydrogenation of single-walled carbon nanotubes.

Plasma-treated single-walled carbon nanotubes were studied by Raman spectroscopy, electron and optical microscopy. The estimation of sample hydrogenation is a change in the ratio of peak intensities D and G measured using Raman spectroscopy [5]. A change in the D+D` peak was also observed, which corresponds to the bonding of hydrogen to the lattice of a single-walled carbon nanotubes [6]. In addition, there was a decrease in the brightness of the samples after plasma treatment. This can be attributed to a decrease in the conductive properties of carbon nanotubes. The structure observed with an electron microscope after plasma treatment is also preserved.

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INFLUENCE OF ENERGY INPUT MODE INTO DISCHARGE CHANNEL ON EFFICIENCY OF CRUSHING OF QUARTZ RAW MATERIALS *

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The electrodischarge method of crushing using a high-current discharge channel in water is considered as an alternative to the traditional mechanical method for obtaining quartz concentrates with a fraction size of 100–300 μm. Solving the problem of increasing the energy efficiency of crushing is necessary to promote the electrodischarge method in industry.

Experimental and numerical studies of the influence of the energy input mode into the discharge channel on the efficiency of the transformation of electrical energy into mechanical work are carried out. In the experiments, generators with different time constants of the discharge, with a discharge half-period of 0.4–0.9 μs at close levels of stored energy were used. The quartz material was crushed both after thermal weakening and without it. It has been experimentally obtained that the efficiency of crushing quartz raw materials to a fraction of 100–300 μm increases with a decrease in the duration and an increase in the power of the output pulse of the generator. The highest yield of the useful fraction of quartz 100–300 μm was realized on a generator with the lowest time constant of the discharge.

To interpret the results, a hydrodynamic model of the expansion of a conducting channel in a liquid was used, taking into account the processes in the discharge circuit of the generator and the plasma kinetics in the discharge channel [1]. The simulation has shown that a decrease in the time of energy input into the discharge channel with an equal stored energy of the generators provides a large compression pressure amplitude in the wave and a shorter pulse duration. Herewith, the total energy in the acoustic pulse is conserved. Note that experimentally it was not possible to register changes in the pressure pulse. A possible reason for the discrepancy between the experimental and calculated data is discussed in the work.

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VACUUM INSTALLATION FOR ION-PLASMA DEPOSITION OF SOLID OXIDE FUEL CELLS ELECTROLYTE *

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Traditional, well-studied and widely used in practice methods of forming the electrolyte of a solid oxide fuel cell (SOFC) are various powder technologies [1,2]. Despite of their simplicity and low cost, they have limited use in developments, aimed at increasing the power density of the SOFC by minimizing the thickness of the electrolyte. The method of magnetron deposition of thin films is promising for solving this problem [3,4]. Its advantages include the possibility of independent regulation of the main parameters of the deposition process, obtaining coatings of uniform thickness on substrates of a large area with the necessary structural and operational characteristics.

In this regard, an automated vacuum installation has been developed and created for deposition a thin-film YSZ electrolyte and a barrier GDC layer to the anode substrates of the SOFC by reactive magnetron sputtering. The installation includes a vacuum chamber, oil-free vacuum pumping system, systems for cooling, gas distribution, substrate positioning, heating and temperature control, electrolyte thickness control, dual magnetron sputtering systems with Zr/Y and Ce/Gd cathodes, an ion source with closed electron drift, power supplies, and control system. The technological process of a two-layer YSZ/GDC electrolyte deposition is fully automated.

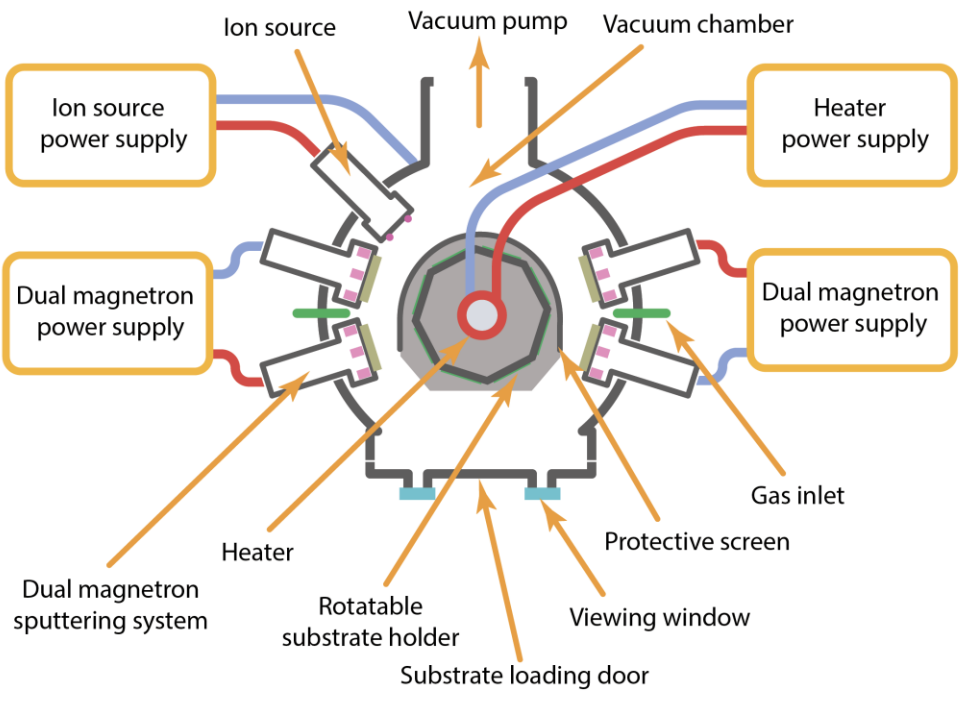

Fig.1. Scheme of the vacuum installation.

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METALLIZATION OF PLASTIC BY MAGNETRON SPUTTERING *

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In recent years, significant progress has been made in the development of rapid prototyping methods, especially 3D printing technologies. Metallization of the surface of printed components makes it possible to replace purely metallic elements made by traditional methods. Three-dimensional printing technologies are increasingly used to create devices for effective control and manipulation of electromagnetic waves. 3D printing technologies were originally applied to RF devices such as waveguides, antennas, filters, and so on. Now, the 3D printing technologies could create components as low-cost and lightweight alternatives within the millimeter wave and terahertz ranges [1]. Usually, the electroless metallization of copper is applied to achieve an electrical conductivity on the plastic surface [2]. This process is generally expensive, toxic and necessitates several complex steps.

In this work, we propose to use environment friendly magnetron sputtering method of Cu deposition on acrylonitrile butadiene styrene (ABS) and high-impact polystyrene (HIPS) plastics manufactured by Bestfilament (Tomsk). The flat 15×15 cm^2 plates were printed on a 3D printer Prusa i3 MK3S with optional MMU2.0 module and coated with a 10 μm thick copper layer, which is much thicker than the skin layer in potential devices (Fig. 1). Plate printing parameters were as follows: print layer thickness 0.2 mm, nozzle diameter 0.6 mm, print speed 60 mm/s, fill factor 100%. Magnetron deposition modes have been found that ensure minimal thermal impact on plastics. Metallized samples were examined in terms of adhesion of the copper layer, its morphology and electrical conductivity.

Fig.1. Example of a 10 μm thick copper film coated plate made of HIPS plastic.

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G3-P-007902

STUDY OF THE INFLUENCE OF A POWERFUL PULSED ION BEAM ON TITANIUM DEEPLY-DOPED WITH ALUMINUM*

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The work studies the impact of high-intensity implantation of aluminum ions and the subsequent impact of a powerful pulsed ion beam on the microstructure and properties of titanium. The high-intensity aluminum ion beam formation was carried out using a method based on plasma-immersion extraction of ions from the free boundary of a vacuum-arc plasma, their acceleration in a high-voltage sheath layer, followed by ballistic focusing. Specimens of titanium were implanted for one hour at a temperature of 900°C with an irradiation fluence of 10^{21} ions/cm^2. Layers with a thickness of about 150 μm were obtained. The energy impact was carried out by a powerful ion beam with an ion current density on the target of 100 A/cm^2. The paper presents data on changes in the elemental composition, surface morphology, and microstructure of ion-doped and energy-modified layers. It has been established that the additional energy impact on the ion-implanted layer of a powerful pulsed beam improves wear resistance by 10 times. The synergy of high-intensity ion implantation of aluminum and the energy impact of a pulsed ion beam improves the wear resistance of titanium by eighteen folds.

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G3-P-008201

MODIFICATION OF SILICON UNDER SYNERGY OF HIGH-INTENSITY IMPLANTATION OF TITANIUM IONS AND ENERGY INFLUENCE OF A HIGH-POWER ION BEAM ON A SURFACE*

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The development of methods for deep ion doping of near-surface layers of semiconductor materials, as well as metals and alloys due to the enhancement of radiation-stimulated diffusion under conditions when the deep layers of the irradiated sample are not subjected to significant temperature effects, is of considerable interest for the practical implementation of technologies for the targeted improvement of the performance properties of parts and products of various destination.

This work is devoted to the study of the features and regularities of the implementation of the synergy of high-intensity implantation of titanium ions at current densities of several hundred mA/cm^2 with simultaneous energy impact on the surface of a submillisecond ion beam with a power density reaching several tens of kW/cm^2.

Ultra-high-dose implantation of titanium ions under conditions of partial heating of the entire sample by the ion beam and significant pulsed heating of the surface provided diffusion doping of silicon with titanium. The studies were carried out depending on the time and fluence of ion implantation.

The methods of Rutherford backscattering of alpha particles, transmission electron microscopy, and X-ray phase analysis were used to study the concentration and spatial distribution of implanted titanium, the microstructure, and the phase composition of ion-doped layers.

It has been shown for the first time that the synergy of high-intensity ion implantation and the energy impact of a high-power-density ion beam, using titanium implantation into silicon as an example, makes it possible to increase the depth of ion doping from fractions of a micron to 6 microns by changing the irradiation duration in the range from 0.5 to 60 min.

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FEATURES OF THERMAL PROCESSES AND THE INFLUENCE OF PULSED HEATING OF SURFACE LAYERS OF TITANIUM ON THE DIFFUSION TRANSFER OF DOPANTS DURING HIGH-INTENSITY ION IMPLANTATION*

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Methods for modification of surface and near-surface layers of materials and coatings by ion beams have prospects for application in many fields of science and technology. The method of high-intensity implantation by high-power density ion beams with submillisecond duration involves significant pulsed heating of the irradiated target's surface layer, followed by its rapid cooling due to heat removal into the material due to thermal conductivity and the implementation of repetitively-pulsed radiation-enhanced diffusion of atoms to depths significantly exceeding the projective ion range.

This paper considers thermal processes' features and the effect of pulsed heating of near-surface titanium layers on diffusion transfer under conditions of synergy of high-intensity titanium ion implantation and energy impact of a high-power density repetitively-pulsed beam on the surface to increase ion doping depth due to radiation-stimulated diffusion under conditions of limited heating of the entire sample.

The paper presents the data of numerical simulation of dynamic changes in temperature fields in titanium and titanium self-diffusion under the action of ion beams with a submillisecond duration and a pulse power of tens of kW/cm^2, fluence of ions in a pulse 1.25×10^{15} ion/cm^2.

It has been shown that the power density range in a pulse from 1.5×10^8 to 3×10^8 W/m^2 at a pulse duration of 500 μs and a frequency of 1 p.p.s. is the most suitable in terms of achieving a noticeable diffusion transfer of the implanted dopant in the target substance with thermally conductive insulation, under the action of a repetitively -pulsed ion beam.

It has been established during the numerical simulation that under conditions of target forced cooling or in the single-pulse mode the beams with pulse power density above $(3\text{-}4)\times10^8$ W/m^2 should produce a noticeable diffusion transfer.

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G3-P-008301

FORMATION OF ALLOYED LAYERS ON THE SURFACE OF VALVE METALS WITH USE OF ION BEAM ASSISTED DEPOSITION OF METALS FROM VACUUM ARC DISCHARGE PLASMA

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Typical representatives of valve metals, on the surface of which an oxide film with a thickness of ~ 10 nm is formed in the air atmosphere, protecting the metal from corrosion in the air and in mildly aggressive environments, are aluminum, titanium and tantalum. The contact between the metal and the oxide film has a one-way conductivity. Metal alloys have the same properties.

Due to chemical inertia, these materials are used for the manufacture of electrodes of electrochemical devices (electrolyzers for hydrogen production, fuel cells), in which corrosion resistance due to the presence of an oxide film is often insufficient. At the same time, the electrodes, along with corrosion resistance, must have catalytic activity in relation to the corresponding electrochemical processes. Increasing the corrosion resistance of products made of alloys of these metals, creating active electrocatalysts based on them, as well as improving the mechanical performance properties of materials can be achieved in the process of alloying the surface with accelerated metal ions.

Layers on the surface of aluminum, aluminum alloy, titanium and tantalum was formed by ion beam assisted deposition (IBAD) of metals. Formation of layers in IBAD mode, by means of the deposition of metal and mixing of precipitating layer with the substrate by accelerated ($U = 20$ kV) ions of the same metal from metal vapor and ionized plasma of vacuum (~10^{-2} Pa) pulsed electric arc discharge, was carried out.

It was found that during IBAD of metals from vacuum arc discharge plasma onto the surface of valve metals multicomponent amorphous layers with a thickness of ~30–50 nm were obtained, including atoms of deposited metals, components of the substrate material, including oxygen of the surface oxide film, as well as hydrocarbon molecules as impurities. When alloying the surface of materials with metal ions having getter properties (Zr, Cr, Er, Dy, etc.), from the residual atmosphere of the vacuum working chamber significant amounts of gases are captured and incorporated into the composition of the formed layer. With IBAD of metals that do not exhibit getter properties (for example, Pt, Ir), the impurity content in the obtained layers is significantly less, their composition contains atoms of the deposited metal and the substrate material. Figure 1 illustrates the data obtained by the example of deposition of metals on the surface of tantalum.

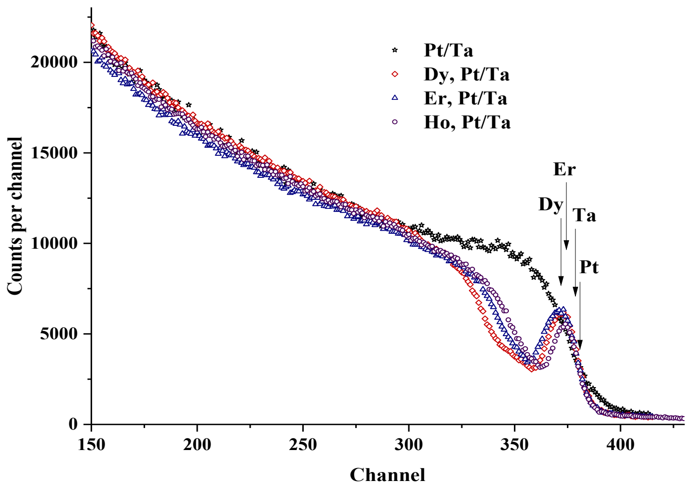

Fig.1. RBS spectra of ^{4}He ions on the nuclei of the atoms of the elements that make up the layers formed on the surface of tantalum during the IBAD of platinum (Pt/Ta), and rare-earth metals and platinum: (Er, Pt/Ta), (Dy, Pt/Ta), (Ho, Pt/Ta).

Based on the location of the RBS signals from the surface of the samples, it can be concluded that during deposition, along with platinum of a rare-earth metal, the content of atoms of the substrate material in the formed layer is insignificant. Such features are also due to the presence of an oxide film on the surface of the valve metal.

RESEARCH OF THE IMPACT OF ION NITRIDING IN THE GLOW DISCHARGE WITH MAGNETIC FIELD ON THE MICROSTRUCTURE AND MICROHARDNESS OF HSS M2 STEEL WITH PREPLASTIC DEFORMATION

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This work was devoted to studying the effect of a magnetic field on the microhardness of HSS M2 steel during ion nitriding in a glow discharge. The samples were preliminarily subjected to intense plastic torsion deformation (IPTD).

Standard methods of metallography, scanning electron microscopy and microhardness measurements were used in the experiments. In addition, the dependence of microhardness on the hardening depth was determined.

It was found that IPTD allows the creation of an ultrafine grain structure in the material, while the magnetic field allows intensification of the ion nitriding process, due to an increase in the ionization number, which leads to an increase in the diffusion layer thickness and microhardness compared to ion nitriding without prior IPTD and without the magnetic field.

These results demonstrate the importance of using magnetic fields in glow discharge ion nitriding. The effects described are of potential interest for improving the mechanical properties of high-speed steels.[1-3]

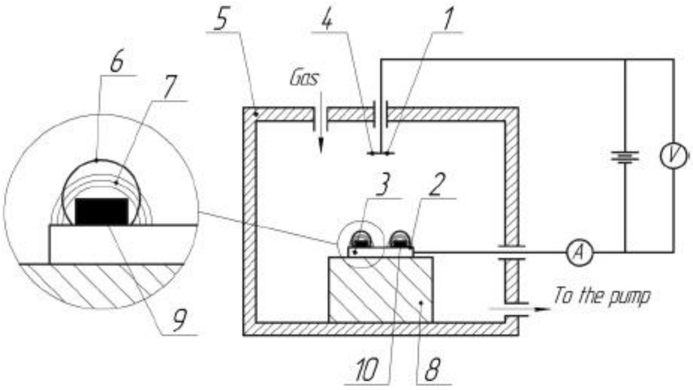

Fig.1 Scheme of the experiment on the installation of ELU-5M: 1 - power supply; 2 - cathode; 3 - neodymium magnets; 4 - anode; 5 - vacuum chamber; 6 - toroidal domain of bright glow; 7 – magnetic field lines; 8 – substrate; 9 – sample with UDS; 10 – sample with PDS.

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THE ROLE OF PRE-TREATMENT CONDITIONS ON FUNCTIONAL PROPERTIES OF 3D-PRINTED TI-6AL-4V STEEL WITH TIN COATINGS DEPOSITED BY MAGNETRON SPUTTERING

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Hydrogen embrittlement is a serious problem for many metals and alloys resulting in its corrosion and degradation of mechanical properties and service life. [1]. Hydrogen barriers can be used to protect materials from hydrogen exposure. Using these barriers, it can be possible to avoid the destruction of materials used, for example, in hydrogen industry [2].

A one of the promising method to protect materials from corrosion and hydrogen embrittlement is surface modification by deposition of protective coatings. Titanium nitride (TiN) coating have a low hydrogen permeability and high permeation redaction factor [3]. In addition, TiN coatings have high wear resistance, which favorably affects mechanical properties of modified metals or alloys.

Nowadays, a lot of tools and elements can be produced using 3D-printing technology [4]. However, such defects such as pores, thermal stress-induced cracks and microstructure heterogeneity can be observed in 3D-printed steels and it is unacceptable for materials applied in industry [5]. So, it is required to determine what pre-treatment conditions can be used to coating deposition as well as to determine the possibility of protection of coated 3D-printed steel from hydrogen embrittlement.

The aim of this work is to determine the role of pre-treatment conditions on functional properties of 3D-printed Ti-6Al-4V steel with TiN coatings deposited by magnetron sputtering. Two types of pretreatment procedures were considered as polishing and sandblasting. Two series of samples were prepared: the first one was polished with SiC paper up to a surface roughness of ~1 μm, the second series was sandblasted with SiC powder (particle diameter of 25-50 μm and pressure of P = 0.23 MPa).

Titanium nitride coatings with a thickness of 1 μm was deposited using multi-cathode magnetron sputtering source having a discharge power density of 20 W/cm^2. Other deposition parameters were following: operation pressure of 0.3 Pa, argon and nitrogen flow rates of 22.5 cm^3/min, substrate bias voltage of -50 V. Titanium was deposited as an adhesive layer with a thickness of 50 nm using followed parameters: power density of 20 W/cm^2, Ar pressure of 0.2 Pa, substrate bias voltage of -50 V.

Several experiments of TiN-coated 3D-printed steel samples were performed. The crystal structure of samples was determined by a X-ray diffraction using a Shimadzu XRD-7000S diffractometer (X-ray tube voltage 30 kV and current 40 mA in Cu Kα radiation). Scanning electron microscopy was used to determine a thickness of TiN coatings and cross-section microstructure. Surface profilogramms of the samples were obtained with a non-contact profilometer Micro Measure 3D Station to identify surface morphology parameters. Gas-phase hydrogen saturation and electrolytic methods followed by uniaxial tensile tests at room and elevated temperatures were applied to estimate a hydrogen resistance of samples.

In common, this study shows dependences of pre-treatment conditions on functional properties of 3D-printed samples of Ti-6Al-4V steel coated with TiN.

The research was funded by Govermental Program (Project № FSWW-2021-0017).

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STUDY OF THE EFFECT OF ASSYMETRIC ROLLING FOLLOWED BY ION NITRIDING ON THE HARDNESS AND STRUCTURE OF HSS M2 TOOL STEEL.

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This study investigates the effects of asymmetric rolling and ion nitriding on the hardness and structure of HSS M2 tool steel. Asymmetric rolling was used to induce a gradient microstructure along the thickness direction of the steel [1,2], while ion nitriding was used to improve the surface hardness[3]. During asymmetric rolling, the heating temperature, the number of passes, the speed mismatch coefficient of the work rolls and the total compression were varied. During nitriding, the temperature and duration of the treatment were varied. The results showed that asymmetric rolling significantly improved the hardness and wear resistance of the steel, while ion nitriding further enhanced its surface hardness. The microstructure analysis revealed that asymmetric rolling led to a fine-grained structure at the surface and a coarse-grained structure at the core, while ion nitriding resulted in the formation of a hardened layer on the surface. Overall, this study provides insights into the potential of combining asymmetric rolling and ion nitriding as a method for improving the performance of HSS M2 tool steel.

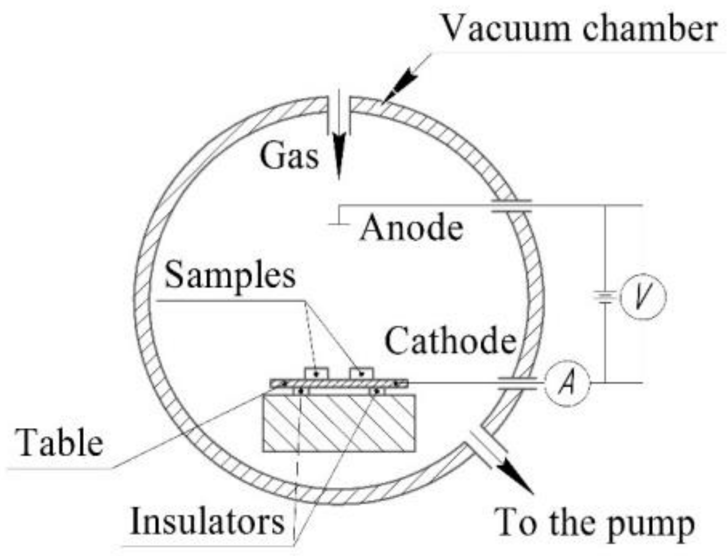

Fig.1. Experimental installation ELU-5M.

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IONIC MODIFICATION OF NITRIDE COATINGS TO INCREASE CORROSION RESISTANCE

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One of the most promising ways to increase the resistance to degradation processes caused by environmental influences or external influences, including aggressive media, is the use of thin-film coatings based on nitrides or carbides [1-3]. This modification method is based on a number of technological solutions aimed at applying protective thin-film coatings to metal parts of devices that are subject to corrosion or external influences that can lead to surface degradation and the appearance of destructive inclusions. In the case of using thin-film coatings that are highly resistant to degradation when interacting with most various external factors, this technology makes it possible to increase wear resistance, as well as service life, which entails a reduction in economic costs and energy resources.

However, despite the prospects for using thin-film coatings as anti-corrosion protective materials, a number of problems remain, the solution of which will increase the service life of materials, as well as increase their resistance to mechanical damage and high-temperature heating. One way to solve this problem is to use the methods of ion or radiation modification using low-energy ions or electron radiation. This modification is based on the hypothesis that, during the interaction of incident charged particles (ions) with the crystal structure of thin films, energy transfer processes, accompanied by energy transformation of kinetic energy into thermal energy, lead to structural changes in film coatings and their hardening. Hardening effects in this case are associated with changes in dislocation density and size factors, which leads to an increase in resistance to external influences, a decrease in the rate of structural degradation as a result of corrosion or high-temperature heating.

In this work, we have studied the prospects for using ionic modification to increase the resistance to external influences of thin films based on titanium nitride obtained by magnetron sputtering. C^{2+} ions with an energy of 40 keV and fluences of $10^{13} – 10^{15}$ ion/cm^2 were chosen for modification. During the experiments, it was found that an increase in the irradiation fluence leads to an increase in hardness values from 10.5 GPa to 13.6–17.2 GPa, depending on the irradiation fluence. In this case, the strengthening of the films is primarily due to a change in the dislocation density, as well as a change in the size factor associated with the processes of recrystallization and grain crushing caused by irradiation.

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FILM COATINGS BASED ON MAGNETRON SPUTTERING AND ELECTRON-BEAM EVAPORATION OF BORON TARGET

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The problem of deposition of boron coatings in electrophysical vacuum devices with consumable solid boron targets is related to the high electrical resistance of pure boron under normal conditions [1]. This does not make it possible to ensure the stable operation of a magnetron discharge with a cathode (sputtered target) made of boron, and in the case of electron-beam evaporation, it complicates the process of beam focusing on a boron target due to the charging of its surface by electrons. To solve the problem of forming coatings from boron, we used two approaches. In the case of magnetron sputtering, a thermally insulated boron target was heated in the discharge itself [2]. Boron has a negative temperature coefficient of electrical resistance; when the target is heated, it decreases and stable functioning of the magnetron discharge is ensured. Electron-beam evaporation of a boron target was implemented using a fore-vacuum plasma electron source that provides beam generation at pressures of 10 Pa. At this pressure, the electron beam generates a dense gas-discharge plasma, the ion flux from which neutralizes the electron charge on the surface of the boron target. This makes it possible to focus the beam on the target and heat it, evaporate, partially ionize vapors, and provide the synthesis of a boron coating from this plasma-vapor phase [3].

A comparative analysis of the deposition of boron coatings on the surface by magnetron and electron beam methods is presented. The main characteristics of the magnetron and electron-beam electric discharge systems that ensure the generation of boron plasma are discussed. Using mass spectrometric measurements, the composition of the plasma during sputtering and evaporation of targets from crystalline boron was determined and analyzed. Boron coating deposition rates were measured for typical device parameters. Test deposition of coatings by magnetron and electron-beam methods was carried out and their properties were studied.

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THE MECHANISM OF OF THE FORMATION OF A MODIFIED LAYER AT LOW-TEMPERATURE ION NITRIDING OF ALLOY Ti-6Al-4V

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Titanium alloys occupy an important place among modem high-strength structural materials due to a unique combination of physical, chemical, mechanical, and technological properties [1, 2].

Of all the forms of chemical heat treatment, ion nitriding is the most effective and promising surface hardening method since it can increase the surface hardness and wear resistance of parts by controlling the saturation process and can also shorten the treatment time considerably. Ion nitriding at temperatures causing an $\alpha \rightarrow \beta$ polymorphic transformation is undesirable, because it is accompanied by coarsening of the structure and worsening of the strength properties.

The work is devoted to the possibility of applying ion nitriding to titanium alloy Ti-6Al-4V at low temperatures. Processing modes for titanium alloys are proposed, which ensure the production of modified layers of the required thickness and quality in order to increase surface microhardness, form favorable surface residual stresses, and maintain a high level of mechanical properties of the base material.

After low-temperature ion nitriding, the presence of a zone of diffusion saturation was revealed, reflecting the rearrangement of the structural-phase state of the titanium alloy Ti-6Al-4V. It is shown that the kinetics of the formation of nitride phases and the formation of residual stresses in the surface layer is largely determined by the temperature of ion nitriding.

The nitride phases were identified by x-ray structural analysis. X-ray photographs of the surface of $\alpha+\beta$ alloys rtitrided at various temperatures show interference lines from three phases: the mononitride TiN (δ-phase) and various modifications of the ε nitride as well as the α-solid solution of nitrogen in the alloy. As the saturation temperature rise the intensity of the lines from the family of crystallographic planes corresponding to the nitride phases increases.

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SYNTHESIS OF BORON CARBIDE IN ELECTRIC ARC PLASMA*

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Boron carbide is an important superhard, refractory material used in various fields [1]. It is characterized by a hardness of up to 48.5 GPa, a melting point in the range from 2620 K to 2740 K, a relatively low density of ~2.52 g/cm^3, and high resistance to chemically active media [2]. There are several ways to obtain boron carbide: carbothermal reduction [3], generation of high-intensity ion and electron beams [4], use of plasmatron technology [5], mechanosynthesis [6], self-propagating high-temperature synthesis [7], etc. One of the important methods for synthesizing materials based on boron carbide is the use of arc discharge plasma both in vacuum and in open-air environment [8]. The advantage of this method is the achievement of high temperatures of the order of several thousand degrees, as well as high heating rates, which makes it possible to obtain the desired materials relatively quickly. In our previous works, we have already shown the possibility of obtaining a material based on boron carbide in the plasma of a DC arc discharge in an open-air environment [9]. However, a significant disadvantage was the contamination of the synthesis product with the electrode material due to electrical erosion processes.

In this work, experimental studies were carried out to obtain a powder containing boron carbide B_4C as the main phase. The studies were carried out on an electric arc reactor using a modernized discharge circuit scheme [10], which was not previously used to obtain boron carbide. Modernization of the discharge circuit consists in the installation of special carbon screens under a negative potential, which make it possible to separate the zone of cathode deposit deposition from the synthesis product. According to X-ray diffraction data, the boron carbide phase B_4C dominates in the synthesis product. Moreover, it was possible to reduce the ratio of the intensity of the main maximum of the graphite phase to the main maximum of the boron carbide phase by 12 times (previously $I_c/I_{B4C} = 3.617$, in this work $I_c/I_{B4C} = 0.285$) using the modernized scheme of the discharge circuit.

Thus, the modernized electric arc reactor, namely, the use of a special geometric design of the discharge circuit, makes it possible to separate the zone of cathode deposit deposition from the synthesis product, thereby reducing the proportion of erosive graphite and ensuring the dominance of boron carbide in the synthesis products.

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INVESTIGATION OF A TITANIUM ALLOY AFTER ION NITRIDING AND COATING DEPOSITION BASED ON Zr-Cr-N*

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Development of scientific and technological progress in the area of creating new generation products of aviation technology requires improvement of existing and development of fundamentally new technological approaches to manufacturing critical parts operating in extreme conditions.

For gas turbine engine parts made of titanium alloys operating in extreme conditions, the surface condition plays an important role, so there is a need to strengthen and protect it. Currently, effective methods of surface modification are nitriding and deposition of protective coatings that increase surface hardness and resistance to erosion wear. Zirconium and chromium nitrides [1-3] are of particular interest as materials for erosion-resistant coatings, which due to high tribological properties, also have high erosion resistance.

However, along with surface protection by coatings, it is necessary to improve the mechanical properties of the base material. One of the most promising ways to increase strength properties is the formation of an ultrafine-grained (UFG) structure by severe plastic deformation [4-5].

This paper presents the results of studying the influence of the structural state of the VT6 titanium alloy on the characteristics of the nitrided layer and the ion-plasma coating of the Zr-Cr-N system.

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ENHANCED RESISTANCE TO EROSION WEAR OF ION-PLASMA COATING ON ULTRAFINE-GRAINED TITANIUM ALLOYS*

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As is known, titanium alloys are a structural material for the manufacture of critical parts in the aircraft engine industry [1]. Such parts during operation are subjected to high alternating loads and increased erosive wear of the surface, changing the geometry of the products and thereby reducing the reliability and durability of gas turbine engines (GTE) [2]. At the same time, the problem of improving the operational properties of parts made of titanium alloys, such as strength, long-term strength, and fatigue fracture resistance, is an acute problem for modern aircraft engine building.

One of the ways to solve the above problems is a combined approach, which consists in increasing the mechanical properties of parts by creating an ultrafine-grained (UFG) structure in their volume by methods of severe plastic deformation (SPD) [3] and deposition of special protective coatings on the surface. Our recent studies of the erosion resistance of ultrafine-grained titanium alloys VT-6 and VT8M-1 with TiVN ion-plasma coating showed an increase in erosion resistance by 2 times compared to the initial structural state of these alloys without a protective coating [4]. The observed effect is associated with the influence of the UFG structure of the alloy on the increase in adhesion bonds (adhesion) of the coating to the substrate (alloy).

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APPLICATION OF JOINT ELECTRIC ARC EVAPORATION AND MAGNETRON SPUTTERING TO OBTAIN THIN FILMS OF Nb_3Sn

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With the development of technology, superconductors are becoming more relevant and more often find applications. These materials are often used as conductors or accelerating elements in charged particle accelerators. Nb_3Sn is a promising material suitable for use in superconducting radio frequency (SRF) cavities as thin films. This intermetallic compound passes into the superconducting state at a temperature of ~18.3 K and acts as a replacement for pure Nb or NbTi [1, 2].

At present, chemical methods are mainly used to obtain Nb_3Sn thin films, but toxic substances are used in the process of obtaining, and harmful phases are formed [3, 4]. Also known is a vacuum method for obtaining Nb_3Sn using layer-by-layer magnetron deposition from two Nb and Sn targets or using a composite target of stoichiometric composition [1]. The composite target is quite expensive, while layer-by-layer deposition is limited by the high sputtering rate of Sn. This requires either a significant increase in the Nb sputtering rate or a significant limitation of the Sn sputtering rate. The rate of Nb deposition can be increased by arc evaporation.

The purpose of this work is to determine the parameters of electric arc evaporation and magnetron sputtering, at which the concentration of Sn in a thin film will be in the range from 19 to 26 at.%, which is necessary for the formation of the Nb_3Sn phase.

Figure 1 shows the scheme of the Nb and Sn layer-by-layer deposition experiment (a) and the dependence of the Sn concentration in the coating on the magnetron power (b). The vacuum chamber is equipped with an electric arc evaporator with an Nb cathode, a magnetron with a Sn target and an ion source designed to clean the substrates before the coating process.

Using energy-dispersive and X-ray diffraction analysis, the elemental and phase compositions of the coatings were studied and it was found that films of the required composition were obtained.

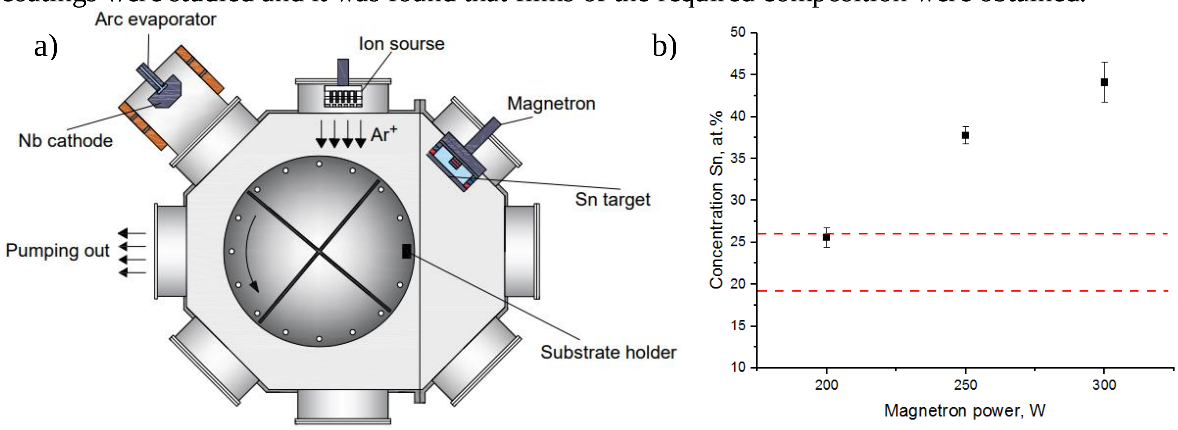

Fig.1. Scheme of the experiment of layer-by-layer deposition of Nb and Sn (a); Dependence of Sn concentration on magnetron power (b).

The work was supported by RSF (project #21-12-00364)

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SYNTHESIS OF SiAlON BY IRRADIATION OF A LOW-TEMPERATURE PLASMA OF A POWDER MIXTURE OF AlN, SI_3N_4, AND Al_2O_3

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Study of substances in extreme states under the influence of high-enthalpy energy flows interesting as for fundamental science, and for solving applied problems. The use of plasma-chemical reactors for the synthesis of ceramic materials is a very promising method. Plasma-chemical reactors have high power and high thermal energy density in the arc. According to calorimetry data mass average enthalpy *Hg* plasma jet on the cut of the output section of the nozzle of the anode node, which is in the range from 24132 to 35739 kJ/kg, which corresponds to the average mass temperature T_{g0} = 6100÷7300 K, cause the achievement of high temperatures in the reactor [1]. This makes it possible to conduct chemical processes with high speed and productivity in a plasma chemical reactor.

The aim of the work was to study the features of thermochemical synthesis in the presence of a high-enthalpy plasma energy flux to a powder mixture. AlN, Si_3N_4 and Al_2O_3**.**

Powders were used as starting materials: β-Si_3N_4, AlN, Al_2O_3, urea salt (H_4N_2CO) and binder liquid glass (Na_2SiO_3). Briquettes with sizes were obtained from these components 45×15 ×45 cm. Then the briquettes were annealed at a temperature of 400 °C.

Plasma-chemical synthesis is carried out using a plasma torch based on the original installation. [1]. Operating modes used in electroplasma installation, made it possible to obtain specific heat fluxes ranging from 1 to $2 \cdot 10^6$ W/m^2.

X-ray structural study was carried out on diffractometer SHIMAD ZUXRD-7000S using $Cu_{K\alpha}$ radiation.

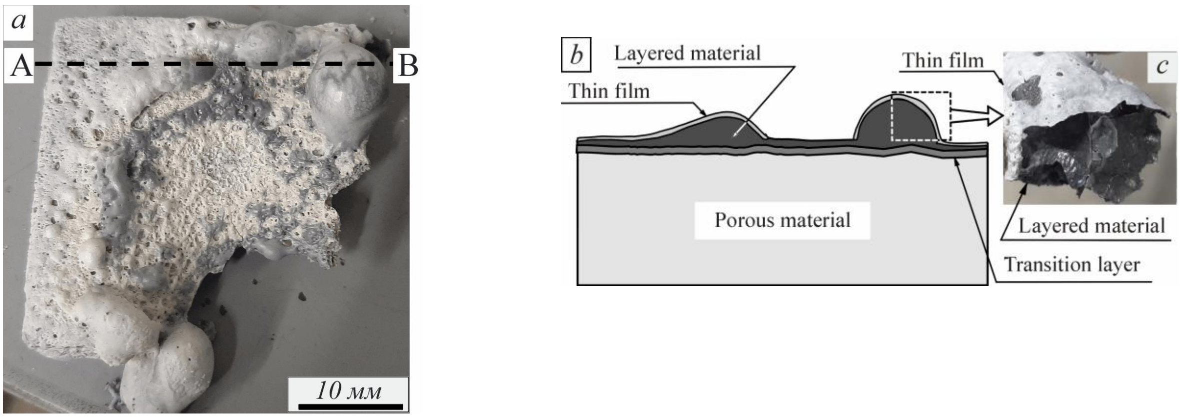

Fig. 1. *a* – photograph of a sample exposed to thermal plasma flows; b – cross-sectional diagram of the sample along the line AB in the photograph (*a*); *c*– photo of a section of a fragment of a bulge on the surface of the sample

The photograph shows the results of the interaction of the plasma flow with the sample. It can be seen that the dynamic interaction of the plasma flow with the sample led to significant erosion of the sample. As a result, a crater was formed at the site of this interaction. At the same time, there is a significant change in the morphology of the surface. Bulges close to spherical shape are observed on the surface of the sample. The surface layer of the sample has a complex structure (fig. 1 *b, c*).

Based on a qualitative X-ray phase analysis, it was established, that the main phase of the porous material is β-SiAlON of composition Si_5AlON_7 ($Si_{6-z}Al_zO_zN_{8-z}$, z = 1 with hexagonal system (Pearson symbol *hP*14, space group $P6_3/m$)).

This work was supported by the state assignment of the Ministry of Science and Higher Education of the Russian Federation (project number FEMN-2023-0003)

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MODIFICATION OF POLYMER ARTIFICIAL VESSELS WITH TISIN COATINGS BY DUAL MAGNETRON SPUTTERING FOR CARDIOVASCULAR APPLICATIONS*

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Cardiovascular diseases in particular atherosclerosis of arteries leading to pathologies such as stroke [1], myocardial infarction [2] and coronary heart disease [3], is a one of the most common causes of death. Surgical restoration of blood flow in a damaged vessel by replacing the affected area with an artificial vessel allows a restoration of blood flow preventing death or reducing consequences of pathologies.

One of the main problems of artificial blood vessels is the low rate of vessel endothelialization. The endothelial layer provides an interface between blood and surrounding tissues. The effective way to accelerate a process of endothelialisation of an artificial vessel is to form a thin inorganic coating on surface of the artificial polymeric vessel to create conditions for improved adhesion and proliferation of endothelial or stem cells.

Thin titanium nitride (TiN) coatings formed by magnetron sputtering on surface of metal alloys are well known to improve cell adhesion and proliferation on the modified surface of metal vascular stents [4]. Doping TiN coatings with Si allows can be used to increase a wear resistance and corrosion resistance to various aggressive media, hemocompatibility and to stimulate a proliferation and spread of endothelial cells.

Currently no studies are focused on a possibility of functionalization of vascular grafts made of fluoropolymer materials by forming thin TiSiN coatings using magnetron sputtering. Accordingly, the optimal process parameters are also not previously described in a literature. So, the aim of the present work is to study a possibility of modifying the surface of vascular grafts made of fluoropolymer materials and to investigate the effect of deposition time on physical and biological properties of the modified graft samples.

Vascular grafts were obtained using a 6 wt.% solution of a copolymer of vinylidene fluoride with tetrafluoroethylene and polyvinylidene fluoride at a ratio 4:1 in acetone and dimethylacetamide in a ratio of 4:1. The graft surface was modified using a dual magnetron sputtering system equipped with Ti (99.9%) and Si (99.99%) targets having a power density of 31.5 and 1.6 W/cm2 for Ti and Si targets, respectively. Other deposition parameters were following: operation pressure of 0.5 Pa, argon and nitrogen flow rates of 23 and 59 cm3/min, respectively. The morphology was investigated by a scanning electron microscopy. The elemental composition of surface of samples was investigated by an energy-dispersive X-ray spectroscopy. The contact angle and surface free energy components were calculated using the Owens–Wendt–Rabel–Kaelble (OWRK) method using the lying drop method on the DSA 25 device. Biocompatibility testing of vascular grafts was performed for a cell culture of human multipotent mesenchymal stem cells (MMSCs) and repeated again after 6 months.

This study presents a modification of polymer vascular grafts by deposition of TiSiN coatings leading to a significant enhancement of biocompatibility compared with the untreated sample.

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GLASS CERAMICS BASED ON SPINEL $MgAl_2O_4$, PRODUCED BY THE PLASMA MELTING METHOD*

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Glass ceramics (glass-ceramic materials) occupy a special place in the production of volumetric composite ceramic materials of the traditional class and in high-tech areas of technology [1]. Despite the widespread use of glass-ceramic materials, their production is still a difficult scientific problem. In addition, crystallized samples may have an uneven structure, which worsens their properties. The purpose of this work is to study the possibility of synthesizing glass ceramics based on $MgAl_2O_4$ with silicon dioxide content from 10 to 50 wt %.

As a source of magnesium oxide MgO, aluminum oxide Al_2O_3 and silicon dioxide SiO_2, common natural raw materials were used: magnesite, boehmite and quartz sand, respectively, of the listed oxides. The formulations prepared were numbered as SP-1, 2, 3, etc. For example, index 1 corresponds to 10 wt. % silicon dioxides in the charge. Experimental studies were carried out on an electroplasma stand [2], which is based on the use of thermal plasma energy for melting solid-phase materials. Melting was carried out in a graphite crucible 60 mm high and 25 mm in diameter. The filling weight was 10 g. The synthesis of samples was carried out at a power of 12 kW for 90 s.

Fig. 1 presents the results of X-ray phase analysis of the obtained melting products from the studied compositions. It has been established that in samples SP-1 and SP-2, where the content of silicon dioxide SiO_2 does not exceed 20 wt. %, no phase formations occur, binary compounds of the type (2MgO SiO_2, MgO SiO_2, $3Al_2O_3$ $2SiO_2$) have not been identified.

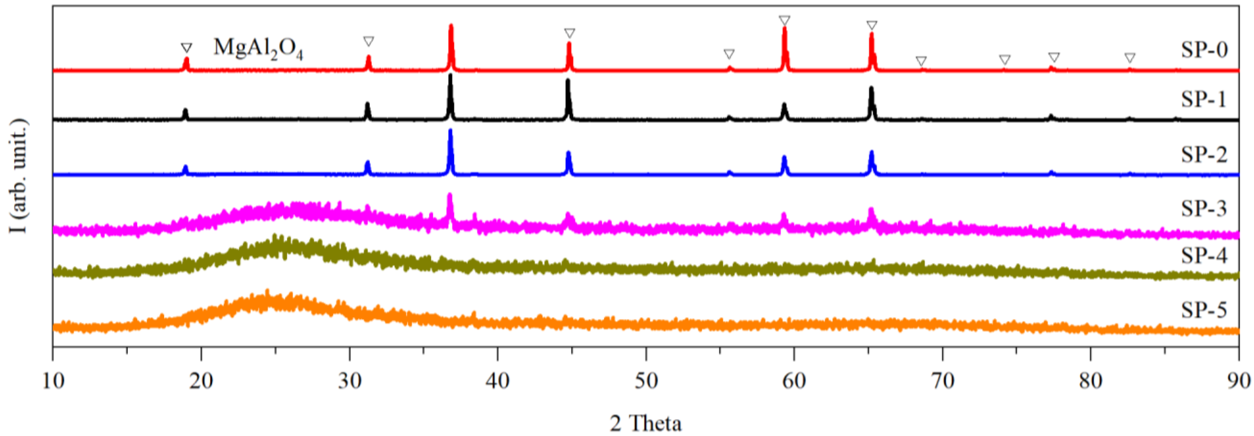

Fig. 1. Experimental XRD of synthesized samples in thermal plasma environment

With an increase in the content of silicon dioxide from 30 to 50 wt. %, the influence of SiO_2 is significant, quasi-amorphous phase is formed in the structural matrix of the material. At the same time, weak intensities of the stoichiometric crystalline phase of $MgAl_2O_4$ are traced in sample SP-3 at $2\theta = 36.6$; 44.7; 59.3; 65.4°. Samples SP-4 and SP-5 are characterized as a material consisting of a quasi-amorphous phase and it is impossible to determine the amount of dissolved $MgAl_2O_4$ in the synthesized samples using X-ray phase analysis. It should be noted that as SiO_2 increases, the diffusion halo tends to narrow and shows the dominance of Si^{4+} atoms during lattice formation.

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HIGH-ENTROPY CARBIDE AS A CATALYST FOR HYDROGEN PRODUCTION BY WATER SPLITTING

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The deterioration of the environmental situation and the limited fuel resources make it necessary to look for new methods of generating energy. Hydrogen energy is an excellent solution to this problem, but it has its own unresolved problems. The reaction of hydrogen evolution with the help of electrochemical splitting of water is a sustainable option for hydrogen production [1]. But the use of electrocatalysts based on noble metals significantly increases the cost of the process. The small distribution of such metals also plays an important role, which forces us to think about alternative candidates for the role of a catalyst. One of the possible options are transition metals, their phosphides, chalcogenides, nitrides, and carbides [2], and in particular WC, Mo_2C, and VC due to properties similar to those of platinum: a high electron density of state at the Fermi level and an extended d band. [3-5]

In recent years, research has been actively carried out in the field of high-entropy carbides. High-entropy carbides are an equimolar multicomponent single-phase solid solution containing 4 or more main components in almost equiatomic ratios [6]. Due to their properties, HECs can become a worthy replacement for platinum-based catalysts. The study by Shiyu Niu et al. [7] confirms the possibility of obtaining and using high-entropy carbide (MoWVNbTa)C as a catalyst in the hydrogen production reaction, while the catalytic properties are superior to those of conventional carbides.

One of the ways to synthesize high-entropy ceramic materials is electric arc synthesis. Our scientific group is implementing this method in an open air environment with the achievement of the effect of shielding the reaction volume by the generated flow of carbon dioxide and monoxide gases, which makes it possible to abandon vacuum equipment, simplify the construction of an arc reactor, and thereby increase the energy intensity of the installation and reduce the cost of the product. The production of high-entropy carbides using this technology was successfully implemented using the example of the material $TiZrNbHfTaC_5$ [6, 8–9].

The synthesis of high-entropy carbide of composition $MoWVCrNbC_5$ was carried out. According to X-ray phase analysis, a material with a cubic structure of the NaCl type was obtained. This material can also be used as a catalyst to produce hydrogen by water splitting.

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STUDY OF INTERMETALLIDES' FORMATION IN SN-FE LAYERED SYSTEM

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In the present work the investigations of thermally induced processes of phase formation in two-layered systems Sn(4 μm) – Fe(10 μm), obtained by ion-plasma sputtering; have been carried out by methods of Mössbauer spectroscopy at ^{119}Sn and ^{57}Fe nuclei.

The application of a Tin coating 4 μm thick onto a substrate of α-Fe was performed on an Argamak setup (Institute of Nuclear Physics, Republic of Kazakhstan) employing the method of ion-plasma sputtering [1]. The substrates were prepared from a bar of armco iron (99.8% Fe) by rolling to a thickness of ~10 μm using special rollers, with subsequent homogenizing annealing at a temperature 850°C for 3 h. Sequential isothermal annealings at 650°C with a duration of up to 20 h were carried out in a vacuum furnace with a residual pressure of 6×10^{-6} mm Hg. Mössbauer spectroscopy was employed as the investigation method. The Mössbauer measurements were conducted on an MS1104ME spectrometer in the absorption geometry at room temperature. $^{57}Co(Rh)$ with an activity of ~30 mCi served as a source of γ-quanta. The spectrometer was calibrated against the standard sample of α-Fe. The experimental spectra were processed using the techniques of restoration of distribution functions of hyperfine parameters of partial spectra and a model identification method [2].

The Mössbauer spectrum of the layered Sn-Fe system in the initial state is a Zeeman's sextet. Thermal annealing at 650°C temperature leads to the appearance of additional lines of the magnetically ordered phase with substantially smaller fields. Processing the spectra using the method of recovering the distribution functions of the magnetic field (fig.1) showed the appearance of an intermetallic phase with parameters characteristic of the intermetallic compound FeSn at first, and then, with an increase in the duration of annealing, the phase Fe_3Sn_2. The dependence of the relative intensities of the partial spectra for the forming phases on the annealing duration was obtained.

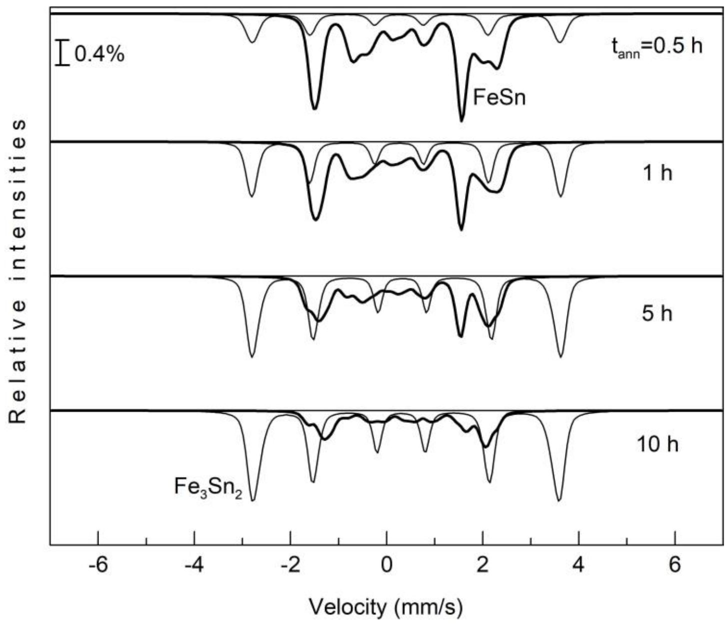

Fig 1. Partial Mossbauer spectra at ^{57}Fe nuclei of intermetallic compounds

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MODELLING OF MOSSBAUER SPECTRA OF ALBE-FE LAYERED SYSTEM

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In this paper, the spectra of binary systems FeBe and Fe-Al [1] were modeled using the methods of the model decoding method of the Mossbauer spectra [2].

Thin Iron foils with Aluminum-Beryllium coating (75 at.% Be+25 at.% Al) after 5-hour isochronous thermal annealing in the temperature range 300-900°C were investigated [3].

For thin Iron samples (thickness ≈10 μm) coated with $Al_{25\%}Be_{75\%}$ thickness ≈2 μm, the values of the average concentration of Al and Be atoms over the entire sample volume were calculated, which are achieved when the impurity atoms are completely dissolved in the α-Fe matrix: 3.4±0.3% for Al and 17.9±1.5% for Be. Using the phase diagram of the binary FeBe system and the "lever rule", the relative contributions of the $FeBe_2$ intermetallic compound and a solid solution α-Fe(Be) of beryllium atoms were calculated. Similarly, for the Fe-Al binary system, the contributions of Fe_3Al intermetallic and a solid solution α-Fe(Al) of aluminum atoms were determined.

The Mossbauer spectra of two-phase intermetallic-solid solution systems were modeled. Taking into account the ratio of the components of the applied coating, the spectra of multiphase $FeBe_2$-α-Fe(Be)+Fe_3Al-α-Fe(Al) systems were obtained. Figure 1 shows the simulated spectra for potentially formed phases at 600°C. For comparison, the experimental spectrum of the layered system $Al_{25\%}Be_{75\%}$(2 μm)-Fe(10 μm) after thermal annealing at 600°C for 5 hours is presented below. Based on a comparative analysis of the calculated and experimental spectra, the sequence of phase formation during thermally induced phase formation in a layered system of $Al_{25\%}Be_{75\%}$-Fe obtained by ion-plasma sputtering is discussed.

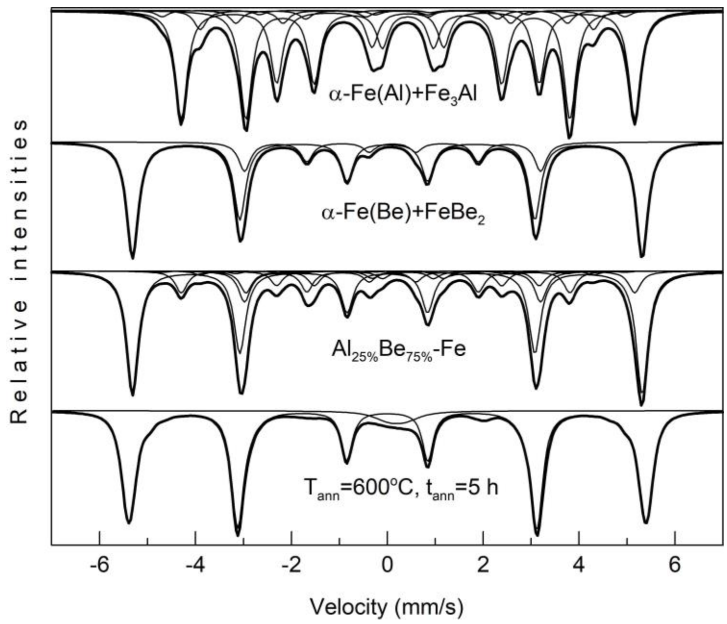

Fig 1. Simulated and experimental Mossbauer spectra at ^{57}Fe nuclei of layered system $Al_{25\%}Be_{75\%}$(2 μm)-Fe(10 μm)

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NUMERICAL SIMULATION OF THE INTERACTION OF A PLASMA JET ON A METAL POWDER IN VARIOUS GASEOUS ENVIRONMENT

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Analysis of the conditions for the formation of spherical metal powders under exposure to plasma jets, based on the accepted concept of physical and the thermal model of the arc is needed to calculate the distribution of velocity vectors flow and temperature during process simulation. In order to correctly obtain the established non-stationary mathematical models, it is also necessary to know the geometric characteristics of the plasma installation, the flow rate of the plasma-forming gas, the electromagnetic parameters of the arc, the properties and composition of the melted metal, and a number of other factors [1].

First of all, the problem was solved, according to the choice of plasma-forming and technical gas, to fill the working chamber of the plasma installation. The properties of gases were calculated, which will be necessary for further mathematical modeling of the physical processes of the plasma arc and its interaction with metal particles. The main parameters that needed to be found are: thermal conductivity, viscosity, heat capacity, density.

Thus, having studied the main operating characteristics of the plasma-forming medium, one can consider the ultimate goal of the study, namely the interaction of a plasma jet on a metal particle [2]. When modeling the process of plasma arc burning and metal melting, it can be seen that at the stage of separation of a particle from a rotating workpiece, it does not interact with the gaseous medium in the process chamber. This eliminates the gas components in the composition of the resulting liquid drop. However, already the stage of cooling and crystallization takes place in the technological chamber in an environment of inert gases of argon and helium; This composition of the gas mixture makes it possible to accelerate the solidification of the metal drop and exclude oxidation of its surface [3].

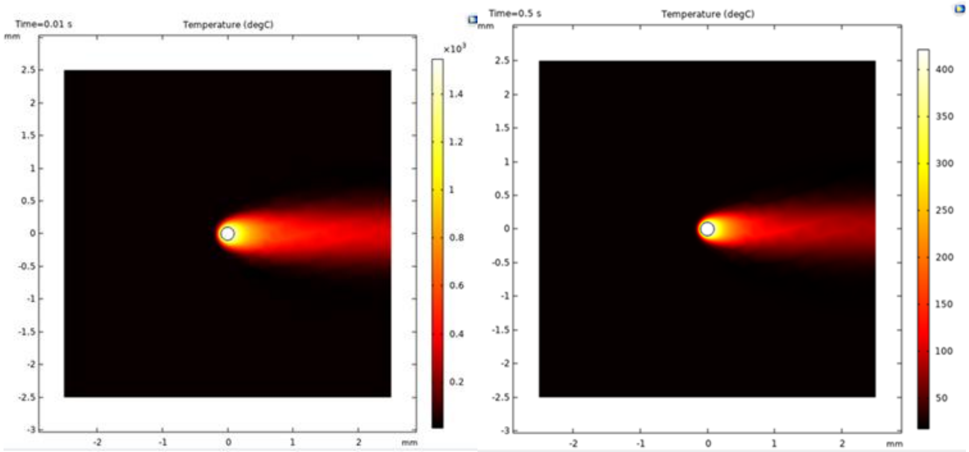

Fig.1. Pattern of particle cooling depending on time in argon a) for t=0.01s b) t=0.5s.

Based on the results of mathematical modeling of particle cooling, it can be clearly concluded that the gaseous medium with a predominance of helium is the best option for filling the process chamber, which serves to cool and collect the resulting metal powder, because in it, cooling takes place 4 times faster than in pure argon.

Knowing the values of the speed of the particle and the time of its cooling, it is possible to calculate the diameter of the process chamber. If we take a cooling time of 0.3 sec and a movement speed of 5 m/s, then the chamber diameter will be approximately equal to 1.5 meters.

The work was carried out within the framework of the research topic under the state assignment of Ministry of Science and Higher Education of the Russian Federation FSEG-2023-0012.

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ARC DEPOSITION OF COATINGS BASED ON ALUMINUM OXIDE IN ELION MODE

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Experiments on the synthesis of a coating based on aluminum oxide using arc deposition and a gridless ion acceleration system were carried out. The studies were carried out on an experimental bench based on the NNV-6.6-I1 setup using two plasma generators: PINK [1] for gas plasma generating and an arc evaporator with an A7 aluminum alloy cathode for gas-metal plasma generating. The substrate temperature was controlled by using the elion [2] mode of plasma-physical devices operation (Fig. 1). The possibility of deposition of a non-conductive coating based on aluminum oxide while maintaining a given temperature by use of the elion mode of plasma-physical devices operation is shown. It is important to note that no negative bias was applied to the substrate during deposition. The substrate temperature affects the phase composition of the resulting coating.

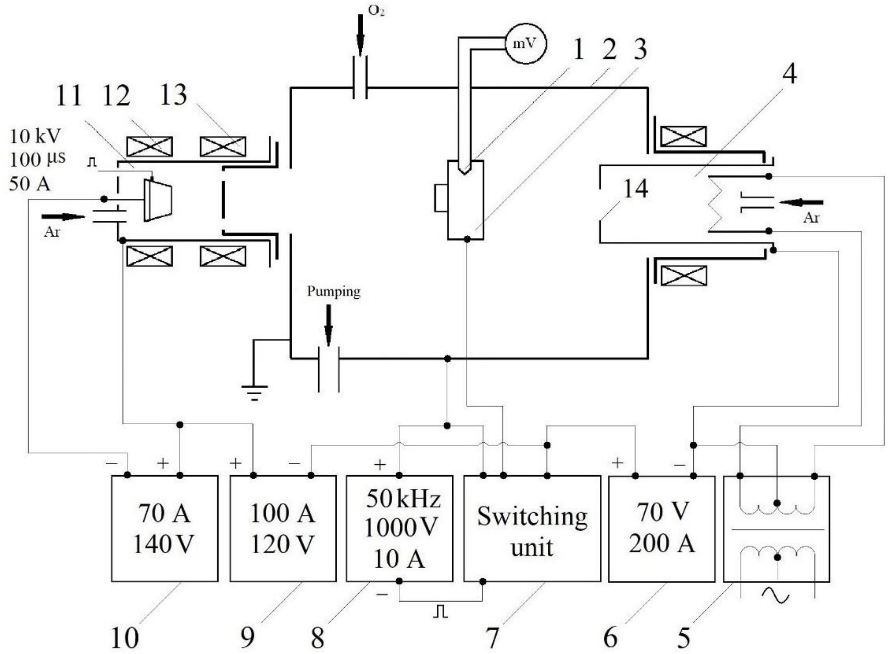

Fig.1. Experimental sheme: 1 – thermocouple; 2-working chamber; 3 – substrate holder; 4 – gas plasma generator; 5 – thermionic cathode heating power source; 6 – gas discharge power supply; 7–switching unit; 8 – bias power supply; 9 - accelerating voltage source; 10 – arc discharge power supply; 11 – ignition electrode; 12-stabilizing coil; 13-focusing coil; 14 – diaphragm

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FORMATION A PRESET TEMPERATURE FIELD OVER MATERIAL DEPTH WITH CONTROLLED HEATING AND COOLING RATES FOR SURFACE ENGINEERING BY MILLISECOND ELECTRON BEAMS *

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The impact of pulsed electron beams on metal and metal-ceramic materials makes it possible to form non-equilibrium structures that give the surface improved tribological and strength characteristics that are not achievable by traditional heat treatment methods. Electron beams with power densities sufficient for melting are used in complex methods of electron-ion-plasma processing, for example, for alloying the surface of steel from a coating [1, 2]. In the plasma source of electrons based on the arc discharge "SOLO" [3], low-inertia control of the current of a beam of megawatt power was achieved by changing the discharge current [4] and by means of grid control. The possibility of a controlled change in the sample surface temperature during an impact pulse with a duration from tens of microseconds to a millisecond has been experimentally shown.

This work is a continuation of a series of studies aimed at creating equipment and approaches for synthesizing materials with predetermined properties. A processing algorithm is proposed, which includes the stages of analysis of possible phases and structures that can improve the properties of the future product. The elemental composition of the original steel can be supplemented by alloying from the coating. Based on previous studies, as well as known data on the required concentrations of elements, temperature and time of formation of structures of interest, processing requirements are put forward: the required range of concentration of alloying elements (if required) and the time dependence of temperature with allowable deviations. If early studies did not involve measuring the temperature dynamics during the exposure pulse, such a dependence is determined by mathematical modeling based on the thermophysical parameters of the material, the specified processing modes and the depth of the modified layer. At the second stage, the change in the impact power density that most satisfies the set requirements is selected by mathematical modeling methods, the temperature field is constructed at different points in time, the temperature change on the surface is calculated, and the possible depth of modification is predicted. At the third stage, using the experimental dependences of the beam diameter, the fraction of the ion current in the accelerating gap current on the generation parameters, the emission coefficient, and also taking into account the limitations of the power supply systems, the dependence of the plasma cathode discharge current on time is determined, which must be set in order to implement the calculated temperature field.

It should, however, be understood that the scatter of the input parameters of the simulation and the insufficient accumulated experimental base in some cases suggest the selection of processing modes to achieve the expected result. First, the experiment measures the surface temperature of the material during exposure. If it differs from the theoretical one, the discharge current setting is changed, the possible causes of the discrepancy are analyzed, and the model is corrected. Secondly, the values of the surface temperature themselves vary at the moment of time with an increase and decrease near the calculated value. The approach formulated in this way makes it possible to form a predetermined temperature field in the material being processed and, with correct prediction, to impart predetermined improved properties to the surface.

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HIGH TEMPERATURE STRUCTURAL-PHASE TRANSFORMATIONS IN 3D PRINTED TITANIUM ALLOYS*

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Nowadays, special attention is paid to the research and design of additive technologies for manufacturing parts from different metals including titanium-based alloys [1]. Among the various additive technologies, wire-feed electron beam additive manufacturing (EBAM) seems one of the most prospective technologies for fabrication of industrial large-scale component blanks as well as repairing damaged or worn parts. However, the mechanical properties of wire-feed EBAM titanium alloy samples are significantly inferior to those of samples produced by electron beam melting or selective laser melting due to a much coarser size of columnar prior β grains transformed into a lamellar α-morphology [2].

A balanced improvement of tensile strength, ductility and fracture toughness of α + β titanium alloys can be achieved through heat treatment at defined processing parameters The different types of heat treatment process that includes homogenization, solutionizing, followed by water or oil quenching and aging can vary widely the microstructure and mechanical properties of titanium-based alloys. For example, high strength in α + β titanium alloys can be developed via solution treatment followed by aging caused the equiaxed fine microstructure to appear. Coarse α colonies usually formed during β heat-treatment, in turn, is expected to increase fracture toughness but decrease in ductility of the alloys. Evidently, the pattern of α and β phase formation during heat treatment of titanium-based alloys strongly depends on the stability of the phases. However, non-equilibrium microstructure is exactly one of the grate disadvantages of additive manufacturing along with poor part surface finish, residual stresses, distortion, etc. In the present work, the phase transformation pathways in wrought and 3D printed titanium alloys at different structural states are studied in situ during heating using differential scanning calorimetry (DSC), X-ray diffraction and high energy synchrotron diffraction analysis.

Ti-6Al-4V titanium alloy widely used in biomedical and aerospace applications due to their high strength-to-weight ratio, high fracture toughness and corrosion resistance, and Ti-5Al-3Mo-V titanium alloy that has an excellent superplastic formability were used as a material for investigation. Wrought and EBAM-fabricated Ti-6Al-4V and Ti-5Al-3Mo-V samples subjected to heating were in the as-received state and after solutionising at 900 or 950 °C for 1 hour followed by water quench and aging at 500 °C in vacuum for 12 hours.

The initial microstructure of the wrought and EBAM samples were studied using optical, scanning and transmission electron microscopy as well as electron backscattered diffraction and energy-dispersive X-ray microanalysis.

DSC heating curve of the EBAM Ti-6Al-4V and Ti-5Al-3Mo-V samples shows endothermic DSC peaks corresponding to the diffusion-controlled α′ martensite decomposition and the allotropic $\alpha \rightarrow \beta$ transformation.

High-resolution synchrotron XRD pattern and conventional XRD pattern obtained with CuKα radiation during the heating up to 1100 °C evidence the XRD peaks shift towards lower 2θ values mainly due thermal expansion of crystal lattice to a higher lattice parameter. Moreover, integrated intensities of diffraction peaks for α phase reduce and β increase due to the allotropic transformation. Finally, the splitting of α′ phase peak under heating is observed due to $\alpha' \rightarrow \alpha+\beta+\alpha''$ phase transformation.

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CERMET COATINGS PRODUCED BY VACUUM-ARC EVAPORATION OF A HIGH-ENTROPY ALLOY*

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High-entropy alloys (HEA) hold much promise for materials science. Ceramic materials based on HEAs are sometimes referred to as a separate family of HEAs. However, as noted in, these materials are not metal alloys but are metal-like compounds in which metallic bonds between metal atoms coexist with ion-covalent bonds between metal and nonmetal atoms. It was found that HEAs and ceramic materials based on them have a number of remarkable properties (high corrosion resistance, excellent mechanical characteristics at high and low temperatures, high wear resistance, high strength and plasticity, high hardness, etc. It is expected that their field of application will become very extensive in the near future. In most cases, ceramic materials, including those based on HEAs, are used for various types of coatings. Among many types of coatings, of great interest are multilayer coatings consisting of a combination of layers with different elemental compositions and, therefore, having different physical and chemical properties depending on the thickness and composition of each layer. Of great practical interest are multilayer coatings with alternating metal and ceramic layers. Coatings of this type have higher rigidity compared to metals and higher fracture toughness compared to single-phase ceramics.

The study presented in this paper was aimed to analyze the structure and properties of two-layer HEA-based cermet (TiNbZrTaHf)N + TiNbZrTaHf) coatings produced on solid substrates by plasma-assisted vacuum-arc deposition.

In addition their phase state and structure were analyzed on an XRD-6000 diffractometer in CuKα radiation and on the VEPP-3 storage ring in synchrotron radiation (INP SB RAS) under normal conditions. The software was MAUD (structural analysis) and Fityk v.1.3.1 (data processing). The heat resistance of the coatings was measured by real-time X-ray diffractometry in synchrotron radiation on the VEPP-3 storage ring (Anton Paar HTK-2000 high-temperature X-ray chamber, OD-3M-350 one-dimensional position-sensitive detector, Fityk v.1.3.1 data processing software). The measurements were performed in air at an operating wavelength of 0.172 nm, temperature of 30–1300°C, specimen heating rate of 15°C/min, and exposure time of 1 min per frame.

A plasma-assisted vacuum-arc deposition method has been developed to produce TiNbZrTaHf + (TiNbZrTaHf)N cermet coatings based on a high-entropy alloy from a multicomponent gas-metal plasma generated by evaporating a multielement cathode of high-entropy alloy. The (TiNbZrTaHf)N nitride layer had an fcc lattice with the lattice parameter a = 4.5084 Å (D = 75 nm, $\Delta d/d = 3.6\cdot10^{-3}$). The cermet coating had a nanocrystalline structure with a crystallite size of 2.5–4 nm, regardless of whether the layer was metal or ceramic. It was found that transition layers were formed between the substrate and the metal layer and between the metal and the ceramic layers. The hardness of the cermet coating was 36.7 GPa and its Young's modulus (at a Poisson's ratio of 0.25) was 323 GPa. The wear parameter of the (TiNbZrTaHf)N + TiNbZrTaHf cermet film was $2.9\cdot 10^{-5}$ $mm^3N^{-1}m^{-1}$ and its coefficient of friction was 0.71.

The advantages of the plasma-assisted vacuum-arc deposition method are the ecological safety of the process and the possibility of complete automation of the cleaning of the substrate surface before coating deposition. The method makes it possible to realize plasma-ion deposition to produce HEA films of required elemental composition. It also enables a step-by-step formation of metal, cermet, and ceramic films and coatings with strictly controlled thickness and elemental composition.

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INFLUENCE OF BREMSSTRAHLUNG ON THE HEAT BALANCE OF HIGH-TEMPERATURE PLASMA

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When the plasmoid is compressed by a plasma/solid liner or laser beams/jets and heated almost adiabatically to the conditions of combustion, the magnetic field is compressed too, increasing its values to the level of megagauss. Compression is considered almost adiabatic due to the presence of a mega-gauss magnetic field, which restrains electronic and thermal conduction, reduces losses by several orders of magnitude; the plasma density at the center remains relatively low, so the losses due to bremsstrahlung are low.

As a result of considering the processes occurring in a system with plasma jets to calculate the main parameters included in the power balance and making the main contribution to energy and physics, it was concluded that the characteristics of the magnetic configuration can significantly affect the confinement of the plasma core and, accordingly, the energy data of the system. And one of the main specific losses in the heat balance of the plasma core are radiation losses P_{rad}.

Braking losses are soft X-rays that cannot be directly converted into electricity, as is possible in the case of charged particle energy or cyclotron radiation. Bremsstrahlung is the main radiation mechanism at temperatures of several kiloelectron volts (keV) and can be estimated with good accuracy for both epithermal particles and nonthermal electrons [1–10].

The bremsstrahlung power depends on the temperature and electron concentration and does not depend on the shape and size of the plasma formation, in contrast to cyclotron losses, which are also determined by the values of the magnetic field, which is essential for the magneto-inertial regime [11–15]. But taking into account the current level of development of science and technology, it is believed that cyclotron radiation almost completely returns to the plasma, since average absorption of radiation by plasma during multiple reflections from walls ~ 0.9. Or in other words, the coefficient of reflection from the walls is ~ 0.9, i.e. the power of cyclotron losses can be neglected.

For the operating temperatures of alternative fuel reactors, calculations of relativistic electron bremsstrahlung have been performed and approximating formulas have been obtained [16–19]. The stellarator and compact torus have the highest plasma temperatures and the lowest bremsstrahlung fraction.

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PROPERTIES OF CrAlYN/CrAlYO MULTILAYER COATINGS PRODUCED BY VACUUM-ARC PLASMA-ASSISTED DEPOSITION

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The paper presents the results of a study of CrAlYN/CrAlYO multilayer coatings deposited on VK8 (WC+8% Co) hard alloy. The microstructure, phase composition, roughness, mechanical properties, heat resistance and thermal stability were investigated. The deposition of CrAlYN/CrAlYO multilayer coatings was carried out by vacuum-arc plasma-assisted deposition on an IPU-1 facility equipped with two electric arc evaporators with Cr (99.5% purity) and AlY (1.5 wt.% Y) cathodes, an additional source of gas nitrogen-containing plasma "PINK" and an additional source of gaseous oxygen-containing plasma "PIPK" [1-4]. Before obtaining multilayer coatings, a layer of chromium up to 100 nm thick was deposited on the substrate in an argon atmosphere. A multilayer coating with alternating layers of CrAlYN and CrAlYO was formed by sequential puffing of the working gas mixture (N_2(80%) + Ar(20%)) and (O_2(60%) + Ar(40%)). Based on our previous studies of multilayer coatings [5-7], we chose the basic version of the architectural construction, which includes 32 alternating layers of nitrides and oxides of chromium, aluminum, yttrium, deposited at a working gas pressure of $P_{N2/Ar}$ = 0.4 Pa and $P_{O2/Ar}$ = 0.6 Pa. The negative bias voltage Ub = 50V, 75V, 100V was used as a variable deposition parameter. For comparison, the following options were also studied: 1) a 32-layer coating deposited at Ub = 50 V, with a 2-fold increase in the pressure of the working gas $P_{O2/Ar}$ - from 0.6 Pa to 1.2 Pa; 2) 16-layer coating deposited at Ub = 50V and working gas pressure $P_{O2/Ar}$ = 0.6 Pa.

In the course of the studies, it was found that the resulting CrAlYN/CrAlYO multilayer coatings have a multiphase structure consisting of nitride and oxide phases. The predominant quantitative content is CrN and Cr_2O_3 phases. Phases based on aluminum and yttrium (AlN and $AlYO_3$) are found in much smaller quantities. The CSR size of all phases is in the range from 15 to 19 nm. Microstrains of the crystal lattice of the predominant CrN phases vary from 1.9 to 6, and Cr_2O_3 from 1.9 to 4.8 and depend on the deposition modes. Sample 75V has the minimum microstresses. In addition, studies of physical and mechanical properties were carried out, which showed that the 32-layer coating (50V) has better characteristics compared to the 16-layer CrAlYN/CrAlYO coating.

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INVESTIGATION OF THE INFLUENCE OF THE THICKNESS OF NANOLAYERS OF INTERMETALLIC COATING OF THE TIALN SYSTEM ON THE PHYSICAL, MECHANICAL AND OPERATIONAL PROPERTIES*

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With the development of engineering and technology, the share of newly developed special materials with higher properties - heat-resistant and heat-resistant alloys, composite materials - is increasing. The mechanical processing of such materials with existing metal-cutting tools is associated with great difficulties [1, 2]. High temperatures in the cutting zone, high strength and anisotropy of properties lead to rapid wear or damage to the tool. To solve this problem, various solutions are used, from the development of new cutting tool materials to special hardening methods. One of which is the application of a wear-resistant coating [3, 4]. Among the existing principles for creating functional coatings, the most promising is the concept of multicomponent coatings. Such coatings can satisfy a number of often conflicting requirements. Using this concept, it is possible to create a coating in which compounds of various functional purposes are synthesized in one layer, providing the maximum reduction in the wear rate of the tool under various processing conditions. The properties of the coating are greatly influenced by the thickness of the nanolayers that are formed during the deposition of coatings from two or more single-component cathodes.

The purpose of this work is to study the influence of the thickness of nanolayers during the deposition of coatings on the physical and mechanical properties, as well as on the durability of a metal-cutting tool.

Studies of microhardness, friction coefficient, chemical and phase composition of the coating, sclerometric studies have been carried out and described. Researches of wear of a covering at turning steel 12x18n10t are carried out. Regularities of the influence of the nanolayer thickness on the durability of the metal-cutting tool are obtained.

The results obtained make it possible to compare laboratory studies and production tests, which makes it possible to develop a promising technology for applying coatings to metal-cutting tools.

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INVESTIGATION OF THE OXIDATION OF TWE-LAYER COATING TIALC-YALO

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Increasing the gas temperature in front of the GTE turbine is necessary to increase the power and efficiency of gas turbine engines (GTE). In this regard, it is necessary to protect GTE parts from exposure to high temperatures and gas flow. Protective coatings based on Me CrAlY and ZrO2-Y2O3 are used to protect blades from temperature drops and oxidation [1, 2, 3, 4].

Currently, a widely used material for thermal barrier coatings (TC) is zirconium dioxide, partially stabilized by yttrium, i.e. ≈8 wt. % Y2O3 (8YSZ) [6, 7, 8]. But in recent works, it has been shown that yttrium aluminates are promising materials for fuel assemblies due to their excellent stability at high temperatures, as well as mechanical and thermal properties [5,6]. At high temperatures, yttrium aluminum garnet (eg, Y3Al5O12, YAG) is as stable as Al2O3 [5], which is used for Ni-based superalloys as a thermally grown oxide layer.

Among the various MAX phase systems, some exhibit excellent high temperature performance. The attractiveness of Ti-Al-C MAX phases for high temperature applications is mainly due to their high temperature characteristics and good oxidation resistance due to the formation of aluminum oxide on the surface with good adhesion and stability at temperatures up to 1400 °C.

Oxide films make the Ti-Al-C system a serious contender for high-temperature applications in the aerospace industry.[9] [10] [11] [12].

In this paper, the process of oxidation of the two-layer system TiAlC-YAlO is considered.

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IN SITU STRUCTURAL-PHASE TRANSFORMATION INVESTIGATION OF ZR-1NB ALLOY WITH CR/TA COATING UNDER HIGH-TEMPERATURE OXIDATION

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Currently, there is a lot of research on the development of reactor fuel cladding coatings capable of ensuring safety under accident conditions, such as a loss of coolant accidents (~1200 °C) [1]. In addition, the coated zirconium cladding must remain stable at normal operating conditions (~360 °C) throughout its lifetime.

The most proven coating material is chromium. The Cr_2O_3 film formed by chromium oxidation acts as a diffusion barrier for oxygen [2]. In addition, chromium has a good adhesion property, its modulus of elasticity is twice that of zirconium, which helps to improve the strength of the cladding [3]. However, due to the interdiffusion of chromium and zirconium at high temperatures, a Laves Cr_2Zr phase is formed at the "coating-substrate" interface, resulting in increased diffusion into the zirconium alloy [2].

One of the solutions of this problem is to develop an intermediate diffusion barrier between the main chromium coating and the zirconium substrate [3]. Such a layer should prevent Cr-Zr diffusion, not have a high thermal neutron capture cross-section, and not form eutectics and other compounds with zirconium at high-temperatures. In a number of papers [4,5], the use of tantalum as a diffusion barrier was considered promising because of its low diffusion coefficient and solubility limit in β-Zr. However, until now, the oxidation behavior of the Cr/Ta-coated Zr-1Nb alloy has not been sufficiently investigated.

Thus, the purpose of this work is to study the structural-phase transformations of the Cr/Ta-coated Zr-1Nb alloy under high temperature oxidation.

High-temperature oxidation of Zr-1Nb alloy samples with Cr/Ta coatings in air (1100°C) was conducted. Based on the obtained data from weight gains, SEM, XRD and in situ XRD, a comparative analysis of samples with bilayer Cr/Ta coatings was carried out. The use of protective coatings can significantly reduce the corrosion weight gain (from 93.3 mg/cm^2 for bare Zr-1Nb alloy to ~24.6 mg/cm^2 for Cr/Ta-coated Zr-1Nb alloy with oxidation for 60 minutes). The thickness of residual chromium in samples with Cr/Ta coating after oxidation for 60 minutes (5.4 μm) is greater than in samples with a single-layer chromium coating (~4 μm [6]), which indicates the effect of suppressing the interdiffusion of chromium and zirconium. As a result of high-temperature oxidation, the formation of interdiffusion layers at the interfaces of the chromium coating / tantalum sublayer (0.76 μm at 60 min) and the tantalum sublayer / zirconium alloy (3.96 μm at 60 min) due to the active diffusion of Ta is observed, the thickness of which increases with oxidation time. Diffusion of Ta at the chromium coating/tantalum sublayer interface leads to the formation of an intermetallic Cr_2Ta phase, which is confirmed by X-ray diffraction. Based on in situ XRD, a short-term prevention of interdiffusion of Cr-Zr is observed. The Cr_2Zr phase is formed after two minutes of oxidation at 1250 °C.

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HIGH-TEMPERATURE OXIDATION OF Cr/Mo-COATED Zr–1Nb ZIRCONIUM ALLOY

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Introduction. Currently, chromium is a promising material for the protection of the zirconium cladding of fuel elements during a loss of coolant accident (LOCA) [1]. The main advantage of choosing this coating is that it forms a protective Cr_2O_3 oxide layer on the surface of the zirconium alloy during high-temperature oxidation. This surface layer acts as a barrier to oxygen diffusion into the zirconium alloy. Nevertheless, the interdiffusion of Cr and Zr increases at high temperatures with subsequent eutectic formation (1332 °C) [2]. The solution to this problem may be the deposition of a barrier sublayer between Cr and Zr. Molybdenum is considered as a material that can effectively limit the formation of the Cr-Zr interdiffusion layer for a long time. Molybdenum has a lower diffusion coefficient in β-Zr at high temperatures compared to Cr, good adhesive strength and similar coefficients of thermal expansion to Cr and Zr [3]. Therefore, the aim of this work is to establish the regularities of interdiffusion and high-temperature corrosion of Cr/Mo-coated Zr–1Nb zirconium alloy.

Materials and methods. A bilayer Cr(8 μm)/Mo(3 μm) coating was deposited on the zirconium alloy by magnetron sputtering. Phase transformation investigation was performed by in situ XRD using synchrotron radiation at the "Precision diffractometry II" station on the VEPP-3 electron storage ring in vacuum in the temperature range of 25–1250 °C. High-temperature tests were carried out in steam at 1200, 1330 and 1400 °C for 1000–2000, 120–720 and 120 s, respectively. The weight gain of the samples was measured on a CP 124S analytical balance. The microstructure and elemental composition of the samples after oxidation were analyzed by TESCAN MIRA3 scanning electron microscopy (SEM) with Ultim Max 40 energy dispersive spectroscopy attachment.

Results. In situ diffraction analysis of the Cr/Mo-coated sample showed no significant changes in the phase composition up to 900 °C. Along with the α-Zr→β-Zr phase transition the formation of the β-Zr(Mo) phase stabilised by molybdenum was observed at 1000 °C. At 1200 °C the Mo_2Zr phase was formed, indicating active diffusion of molybdenum into zirconium.

The Cr/Mo-coated samples remained protective state at 1200 and 1330 °C in steam throughout the oxidation time, since the weight gain was an order of magnitude lower compared to the uncoated sample. Increasing the oxidation temperature to 1400 °C did not significantly affect the difference in weight gain between coated and uncoated samples (10–12 mg/cm^2). This indicates a weak protective effect of the coating at this temperature.

SEM results showed no formation of Cr-Zr interdiffusion layer at 1200 and 1330 °C throughout the oxidation time. Thus, a molybdenum barrier sublayer suppresses the interdiffusion of chromium and zirconium at 1200 and 1330 °C for at least 2000 s and 720 s, respectively. At 1400 °C for 120 s oxidation, zirconium oxides and interdiffusion layers with the presence of Cr, Mo and Zr are formed under a thin Cr_2O_3 oxide layer. In addition, cavities were formed at the ZrO_2/α-Zr(O) interface. Consequently, at 1400 °C the use of a molybdenum sublayer does not effectively suppress the interdiffusion of Cr and Zr for 120 s. At this temperature, molybdenum actively diffuses deep into the zirconium alloy and loses its barrier properties.

Conclusion. The molybdenum barrier layer limits the interdiffusion of Cr and Zr during high-temperature oxidation at 1200 °C for 2000 s, as well as at 1330 °C for 720 s. Diffusion of molybdenum at high temperatures leads to the formation of the Mo_2Zr phase at the Mo/Zr alloy interface. After oxidation at 1400 °C for 120 s, the Cr/Mo-coated sample showed a weight gain comparable with the single-layer Cr coating. Significant diffusion of molybdenum into the zirconium alloy indicates a loss of barrier properties of the deposited sublayer.

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INVESTIGATION OF VACUUM ARC COATINGS BASED ON ALUMINUM OXIDE SYSTEM USING ION ASSISTANCE

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To improve the properties of cutting tools, various hardening technologies are used. Coating is one of the most promising and most effective methods for protecting of the contact pads of the cutting tools [1]. Physical Vapor Deposition (PVD) [2] is the most common of the variety of coating options.

Coatings based on aluminum oxide have high thermal and chemical stability at temperatures above 1000°C, therefore, they are widely used for cutting tool inserts [3]. In this work, the coatings were deposited by the vacuum-arc method on an NNV6.6-I1 setup. Vacuum-arc deposition consists in applying coatings in a vacuum by condensing onto a substrate the required material from plasma flows generated at the cathode in the vacuum arc cathode spot [4]. The coating was applied to four samples of hard alloy VK8.

Coating modes included intensive ion support in one of the cases in order to evaluate the influence of the assisting parameters used on the obtained phase composition and properties of the coatings.

Was carried out vacuum heat treatment of samples at different temperatures to change the phase composition of the coating.

The phase composition was estimated using X-ray diffraction analysis. Measurements of the microhardness of the coating were carried out, tribological tests and a scratch test made it possible to assess the nature of wear and the degree of destruction of the coating under the conditions used.

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STUDY OF COATINGS BASED ON TITANIUM ALUMINUM CARBONITRIDES TO INCREASE THE LIFE OF METAL-CUTTING TOOLS

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In this paper, the influence of the ratio of reaction gases when carbonitride coatings of the Ti-Al-C-N system are applied to a hard-alloy cutting tool on the physical-mechanical and operational properties is considered. When coating was applied, a mixture of nitrogen gases N2 and acetylene C2H2 in various ratios was fed into the chamber [1]. The results of the microhardness values showed that the highest microhardness value (2620HV0.05) has a tool coated with a reaction gas ratio of 40:60. According to the results of field tests, it was determined that a coated cutter applied at a gas ratio of 80:20 increases tool life by more than 20 times compared to an uncoated tool and more than 2.5 times compared to a TiAlN coating (N2:C2H2=100:0) [2-4]. According to tribological tests, it was found that the coating applied without nitrogen (N2:C2H2=0:100) has the minimum coefficient of friction kf=0.43 [1, 5]. At the same time, the smallest weight loss corresponded to the results of tool life obtained during full-scale tests. That is, the sample with the coating applied at the ratio of reaction gases N2:C2H2=80:20 had the minimum weight loss [6-8]. Scanning electron microscopy was used to study the front surfaces and transverse sections of cutting tools after turning. Analysis of the chemical composition of the studied tools after the cutting process showed that on a sample with a coating obtained at a ratio of reaction gases of 80:20, the content of coating elements on the surface is higher than that of other coatings, which indicates less tool wear. At the same time, iron is observed on all the studied samples, confirming the sticking of the processed material to the tool.

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ON PROGRESS OF ACTIVITIES OF THE PROJECT «IN SITU METHODS FOR SYNCHROTRON INVESTIGATIONS OF MULTILAYER FUNCTIONAL STRUCTURES WITH UNIQUE PARAMETERS AND PROPERTIES CREATED BY BEAM-PLASMA SURFACE ENGINEERING»[1]

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Accelerating the process of creating of new materials with unique properties is possible only by combining the efforts of scientific, educational and industrial organizations, as well as using tools that contribute to solving fundamental problems facing both the scientific community of Russia and the whole world. It is known that in most cases of using materials in extreme conditions, it is the surface that determines their functional properties and, as a result, the service life of products as a whole. A multiple reduction in the time of development and implementation of new materials, methods and equipment for their production on the territory of the Russian Federation is possible with the use of the most modern methods and techniques of synchrotron research.

A consortium consisting of such organizations as HCEI SB RAS, INP SB RAS, ISPMS SB RAS, TSC SB RAS, Tomsk universities - TPU, TSU, TUSUR, IEP UD RAS, as well as the Ufa State Aviation Technical University and the industry enterprise "Technopark-AT", since October 2021, have been implementing a project on the topic "In situ methods of synchrotron investigations of multilayer functional structures with unique parameters and properties created by beam-plasma surface engineering" within the framework of the Federal Scientific and Technical program for the development of synchrotron and neutron research and research infrastructure for 2019 - 2027".

The objectives of the project are related to each other and, in accordance with Direction 1 "Synchrotron and neutron research (development) in the field of materials science for the development of high-tech production technologies", are focused on creating infrastructure and developing methods for synchrotron and neutron research of structural and functional materials.

The report provides information on the progress of the project, including the most important scientific results obtained using synchrotron radiation, a description of the infrastructure facilities being created for synchrotron research, as well as the progress of the educational component of the project.

[1] The work was carried out with the financial support of the Russian Federation represented by the Ministry of Science and Higher Education (project № 075-15-2021-1348) within the framework of the events № 3.2.1, 3.2.6 and 3.2.9.

G4-O-904404

STATUS OF DESIGNING OF THE BEAMLINE 1-2 "STRUCTURAL DIAGNOSTICS" OF THE SRF "SKIF"

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The report provides information on the current state of affairs in the development and designing of beamline 1-2 "Structural Diagnostics" (BL 1-2) of Synchrotron Radiation Facility “SKIF” as a whole and on its individual elements and systems.

The composition of the BL 1-2, the features of the designed elements and systems are described, as well as the synchrotron research methods planned for implementation at the BL 1-2.

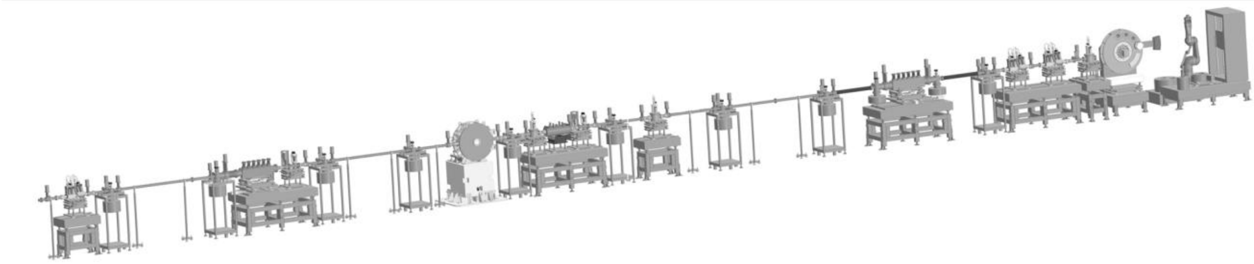

Fig.1. Image of the model of the developed BL 1-2 "Structural diagnostics" of the SRF "SKIF".

EFFECT OF CHEMICAL COMPOSITION ON MECHANICAL PROPERTIES OF ZINC ALLOYS

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In recent years, close attention has been paid to zinc alloys as a bioresorbable material for implants. The medical material must remain biocompatible throughout the implantation and degradation process, i.e. the material must be non-toxic, non-inflammatory, and must not form harmful degradation products. Pure Zn has low mechanical properties, the use of severe plastic deformation does not lead to the necessary strength properties that are required for implants, therefore alloying methods are used to increase the strength properties. Zn has a lower corrosion rate than Mg, which allows alloying with a wider range of non-toxic elements that improve the mechanical properties of the material.

This paper presents the results of studies of zinc alloys of the Zn-Fe-Mg, Zn-Li-Mg and Zn-Ag-Cu systems with different ratios of one of the elements. To maximize the strength properties, heat treatment methods were used, as well as methods of severe plastic deformation. The structure of the obtained samples was studied by transmission and scanning electron microscopy. Comparative studies of strength properties were carried out by methods of measuring microhardness and tensile tests of experimental samples. And also the corrosion properties were investigated by the gravimetric method.

Alloying led to an increase in microhardness in the Zn-Ag-Cu, Zn-Fe-Mg, Zn-Li-Mg systems up to 98 HV, 178 HV and 216 HV, respectively. The use of severe plastic deformation contributed to the refinement of structural elements, the uniform distribution of particles along the boundaries of the material, the increase in the strength of the material and the increase in plasticity. In alloys containing Fe, the specimens failed in the elastic region before and after deformation. The use of severe plastic deformation in Zn-Fe-Mg, Zn-Li-Mg alloys led to an increase in the corrosion rate; in the Zn-1Ag-1Cu system, the corrosion rate decreased.

The paper presents comparative structural studies of zinc alloys and considers the mechanisms for increasing their strength properties.

Studies of zinc alloys Zn-1Fe-1Mg and Zn-2Li-Mg were carried out at the expense of a grant in the field of science from the budget of the Republic of Bashkortostan for state support of young scientists (Agreement No. 1 dated 12/13/2022). The study of Zn-XAg-Cu zinc alloys was funded by RFBR and TUBITAK, project No. 21-53-46017. M.Polenok is grateful to Ministry of Science and Higher Education of the Russian Federation for support within project No. № 075-03-2023-119/1 for youth research laboratory "Metals and Alloys under Extreme Impacts". Authors are grateful to the personnel of the Research Equipment Sharing Center "Nanotech" of Ufa University of Science and Technology for their assistance with instrumental analysis.

IN SITU SYNCHROTRON X-RAY DIFFRACTION DIAGNOSTICS OF PLASMA DEPOSITED COATINGS*

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The coatings of the surface synthesized by means of plasma assisted deposition may strongly change the physical and chemical properties of the surface. Despite of relatively thin coating layer the resistance of the surface to mechanical, thermal and chemical impact increases in several times. Actually the strength and stability of the coating depends on the structure and phase composition of the coating layer. X-ray diffraction (XRD) is the most effective method providing information about structural and sub-structural parameters of the coating deposited.

Synchrotron radiation (SR) produced by charged particles moving along bent trajectory demonstrates a set of properties which make it very attractive for scientific research and high technology applications. The power of SR is several orders of magnitude higher than that of any other source of X-rays. The spectral range extends from vacuum ultra-violet photon energies to hard X-ray region. High natural collimation makes possible to use relatively simple optical elements such as flat perfect crystals for monochromators and analyzers. All these and other features of SR look very useful for In Situ diagnostics of plasma deposited coatings with time-resolved XRD.

The experiments on SR XRD of coatings under normal and non-ambient conditions such as heating in vacuum and atmosphere up to 1300-1500°C were executed at Siberian Synchrotron and Teraherz Radiation Centre at Budker Institute of Nuclear Physics SB RAS, Novosibirsk, Russia. Two beamlines namely “High Precision Diffractometry and Anomalous Scattering” and “High Precision Diffractometry II” were involved into research. The report describes the experimental technique and some results of the measurements. Finally the first results on the study of coating deposition immediately within plasma chamber are represented.

The work on SR XRD diagnostics of plasma assisted coatings will be developed with the creation and introduction of synchrotron radiation facility SKIF [1] which is now under construction close to Koltsovo, Novosibirsk region, and is expected to be accomplished to the end of 2024. The report represents the description of the storage ring parameters, first priority beamlines and second priority beamline “Surface” which is dedicated for study of plasma modification of the surfaces.

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NITRIDING EFFECT ON THE STABILITY AND MECHANICAL PROPERTIES OF THE FETI PHASE: FIRST-PRINCIPLES INVESTIGATION

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To enhance the stability of material surfaces against external mechanical and chemical influences, various surface treatment methods are employed. From technological and economic perspectives, it is reasonable to modify the characteristics of working surfaces according to production needs [1]. This effect can be achieved by applying coatings to the working surfaces. Nitriding is the most widely used thermochemical surface treatment method for improving the mechanical properties of steel [2-5]. Nitrogen enrichment of the surface layers of steel introduces local distortions, which affect structural stability and magnetic properties [6]. The addition of titanium to steel exhibits excellent characteristics for nitriding due to its strong stabilizing effect on intermediate reaction products and a moderate level of nitrogen diffusion barrier [7]. Hence, it is important to understand the role of nitriding on the structural and mechanical characteristics of titanium-coated steels. Based on the above, the aim of this study is to investigate the influence of various atomic concentrations of nitrogen on the stability and mechanical properties of the FeTi phase. Figure 1 shows the FeTi phase, which is considered as a universal model for the iron-titanium mixing zone in titanium-coated steel with different N concentrations and distribution types. By employing computer modeling, the impact of increasing atomic nitrogen concentration on the structural and mechanical properties of titanium-coated steel coatings was examined.

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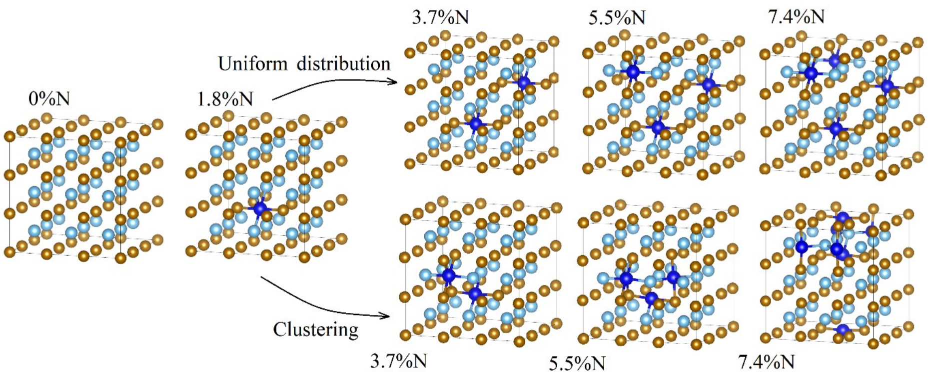

Fig. 1. Fe-Ti supercell containing uniformly distributed and clustered N with the concentration of (a) 0%, (b) 1.8%, (c) 3.7%, (d) 5.5%, and (e) 7.4%.

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VACUUM ELECTRON-ION-PLASMA INSTALLATION VEIPS-1 FOR IN SITU STUDIES OF PROCESSES OF LAYERS AND COATINGS SYNTHESIS BY METHODS OF BEAM-PLASMA SURFACE ENGINEERING USING SYNCHROTRON RADIATION

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The paper presents the vacuum electron-ion-plasma installation VEIPS-1 (Fig.1), produced in 2021-2023 as part of the research program «*In situ* methods of synchrotron studies of multilayer functional structures with unique parameters and properties created by methods of beam-plasma surface engineering».

VEIPS-1 is designed for *in situ* studies of the samples surface directly in the process of coating deposition. For the implementation of coating deposition, the installation has 5 ports for mounting of functional devices. VEIPS-1 has a water-cooling system, gas supply, vacuum system and automation system. The automation system allows you to implement a technical map of the deposition process with an unlimited number of steps. In addition, the installation has X-ray transparent windows for input of the synchrotron radiation beam and output of radiation to the X-ray detector (window captures the sector from 0º to 60º from the SR beam axis).

The installation in a configuration with two arc evaporators, a PINK gas plasma source and a PSCHC source for oxygen plasma generating was launched and tested at the beamline №6 of the VEPP-3 synchrotron radiation source (INP SB RAS, Novosibirsk) in June 2023.

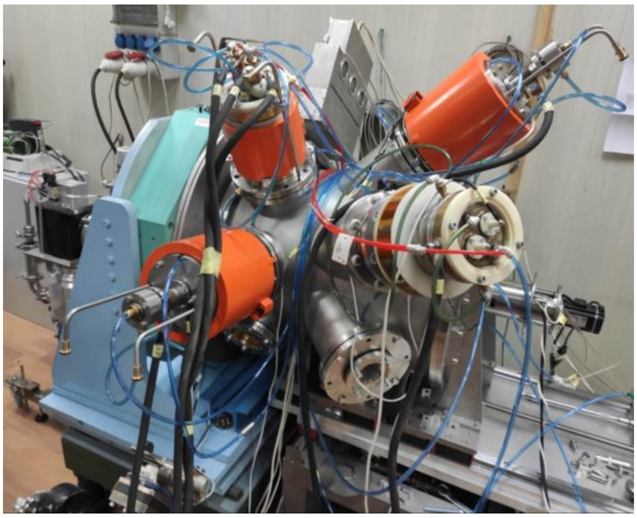

Fig.1. Experimental installation VEIPS-1 at beamline № 6 endstation of the SR source VEPP-3.

The work was carried out with the financial support of the Russian Federation, represented by the Ministry of Science and Higher Education (project No. 075-15-2021-1348) within the framework of event No. 3.2.1.

RADIATION-INDUCED DAMAGES IN ALUMINUM NITRIDE UNDER IRRADIATION WITH HEAVY IONS

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Interest in studying radiation damage and establishing relationships between structural changes caused by irradiation with changes in optical, electronic or thermophysical properties is primarily due to the need to accurately understand the mechanisms of radiation damage accumulation in structural materials, as well as to identify critical factors that can have a negative impact on the timing exploitation of materials[1,2]. Moreover, in addition to the practical significance of studying the mechanisms of radiation damage, such studies are also important from a fundamental point of view, since they make it possible to determine the main mechanisms of the interaction of ionizing radiation with matter, as well as, on the basis of the obtained experimental data, to determine the kinetics of accumulation and subsequent evolution of radiation damage in the material.

The simulation of the accumulation of radiation damage in order to determine the kinetics of changes in the structural and optical properties was carried out by irradiating the studied samples of polycrystalline ceramics with heavy Kr^{15+} ion with a total energy of 147 MeV (1.75 MeV/nucleon) in the range of irradiation fluences from 10^{10} ion/cm^2 to 5×10^{13} ion/ cm^2. The ion flux density was no more than 10^9 ion/cm^2×s, the choice of which was due to the prevention of overheating of the target during long-term irradiation and subsequent destabilization of radiation damage during thermal heating. The choice of the range of irradiation fluences is due to the possibility of modeling single radiation damages, as well as creating areas of overlap of defective regions due to the accumulation of radiation damage along the ion movement trajectory in the near-surface layer of ceramics.

In the course of the studies, it was found that the main structural changes associated with the accumulation of point defects and their subsequent transformation into larger agglomerates occur at fluences above 10^{12} ion/cm^2, which is characteristic of the formation of areas of overlap of defective areas. In this case, the structural disorder has a pronounced anisotropic form when the crystal lattice is distorted, which is primarily due to the difference in the ionic radii of aluminum and nitrogen, as well as the features of the construction of the hexagonal crystal lattice. The deformation distortion caused by the accumulation of radiation damage has a tensile character, indicating the formation of a defect structure in the form of vacancies and primary knocked-on atoms occupying positions in the interstitial space, as well as the possible implantation of ions with the formation of disordered regions.

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SOME FEATURES OF OPTICAL COATINGS DESTRUCTION WITH VUV IRRADIATION*

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For the practical application of ultraviolet (vacuum, extreme) and X-ray radiation, the use of multilayer optical and interference coatings is necessary [1]. At the same time, the impact on the surface of powerful broadband radiation of the VUV spectrum range (10-150 nm) causes evaporation of almost all materials. However, there is currently no systematic information on the interaction of high-intensity VUV radiation fluxes with coatings that can degrade due to the intensification of diffusion processes, chemical transformations, radiation ablation, etc. Problems of obtaining such information are, among other things, a limited number and low intensity of UV/VUV radiation fluxes from such sources [2].

In the presented work, a short–wave emitter based on a coaxial high-current plasma accelerator – a magnetic plasma compressor (MPC) of the erosive type is used as a source of high-brightness broadband VUV radiation [3, 4, 5]. In such devices, a dynamic method of plasma heating is implemented. It is based on the viscous dissipation of kinetic energy of a high-speed dense plasma flow in the front of the shock wave formed during its deceleration. If the discharge is carried out in a gas medium, then the buffer gas acts as a filter for the high-energy component of the plasma emission spectrum and determines the minimum wavelength in the discharge radiation spectrum (“gas modification” of the spectrum). For a discharge in neon, such a wavelength is about 60 nm (21.56 eV), in argon - 76 nm (15.76 eV), in air – 180 nm (≈6 eV). Thus, discharges in inert gases and in vacuum make it possible to realize extreme modes of exposure to irradiated coatings, in which the quantum energy exceeds both the binding energy and the ionization potential of atoms in the sample; an integral (in the entire spectral region) heat flux with a density of up to 0.4-0.9 MW/cm2 comes to the irradiated surface.

The experimental results of the multilayer optical coatings degradation (destruction) when they are irradiated with powerful broadband vacuum ultraviolet radiation of various spectral composition are presented in the report.

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PROPERTIES OF MULTILAYER COATINGS PRODUCED BY VACUUM-ARC SEQUENTIAL AND SIMULTANEOUS SPUTTERING OF ZIRCONIUM AND Ti-B-Si-Ni CATHODES

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The paper presents the results of comparative study of the mechanical properties and heat resistance of a zirconium nitride coating and a multilayer coating obtained by sequential and simultaneous sputtering of zirconium and multicomponent cathode (titanium, boron, silicon and nickel) in a nitrogen-containing medium. Multicomponent cathode was fabricated by self-propagating high-temperature synthesis with simultaneous pressing. The coatings were deposited on the hard alloy VK-8 by the vacuum-arc plasma-assisted method [1-7]. Material science studies of coatings included: measuring the thickness of coatings by calo testing, evaluating the adhesion strength of a coating to a substrate by the Rockwell method and scratch testing, measuring microhardness before and after high-temperature annealing in air at a temperature of 700 °C for 60 minutes, X-ray phase analysis of coatings before and after high-temperature annealing. Multilayer multicomponent coating (Zr+Ti-B-Si-Ni)N was also investigated for heat resistance in real time by X-ray phase analysis using synchrotron radiation. The adhesive strength of the multilayer, multicomponent coating (Zr+Ti-B-Si-Ni)N satisfies the generally accepted quality requirements for vacuum-arc coatings. The residual microhardness of the multilayer multicomponent coating (Zr+Ti-B-Si-Ni)N after high-temperature annealing significantly and noticeably exceeds the microhardness of the ZrN coating after annealing. Data of X-ray phase analysis confirm the high heat resistance of the multilayer multicomponent coating (Zr+Ti-B-Si-Ni)N, which, together with the results of mechanical tests, allows us to conclude that it is promising for practical purposes.

The work was carried out within the framework of the state task of the Ministry of Science and Higher Education of the Russian Federation on topic No. FWRM-2022-0001.

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STRUCTURE AND PROPERTIES OF HEA FILMS SYNTHESIZED BY THE ION-PLASMA METHOD

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The development of alloys, called high-entropy (HEAs), consisting of five or more basic chemical elements of close concentration, which in most cases are single-phase thermodynamically stable substitutional solid solutions, mainly based on bcc or fcc crystal lattice, indicates the emergence of a new paradigm in the design of modern materials [1-4].

The unique functional properties of HEAs (high hardness after annealing at temperatures above 1000 °C, high thermal stability, hydrophobicity, superelasticity, increased resistance to wear, corrosion and oxidation, high rigidity, strength and impact strength, good fatigue resistance) put these materials into the category the most promising [5-7].

The more constituent elements with very different atomic radii (Δ=Rmax-Rmin), the greater the intracrystalline deformation and the higher the probability of formation of an amorphous state of HEAs was first noted in [8].

The purpose of this work was to analyze the structure and properties of HEAs films synthesized by the vacuum-arc with plasma assisted method, which differ in the parameter Δ.

The research material was HEAs films deposited on samples of AISI 304 steel and VK8 hard alloy, having the following elemental composition: TiNbTaHfZr (film No. 1), TiAlCrMoNb (No. 2), and TiAlCuNbZr (No. 3). For film №1 Δ=0.017 nm, for film №2 Δ=0.020 nm, for film №3 Δ=0.032 nm. Using X-ray phase analysis, it was found that films № 1 and № 2 have a bcc crystal lattice. Film № 3 is an X-ray amorphous material.

Transmission electron diffraction microscopy showed that film №1, obtained by sputtering a multi-element cathode, is a single-layer formation with a columnar structure; Films №2 and №3, formed during the simultaneous evaporation of several cathodes, are, due to the formation technique, multilayer systems. The films have a nanocrystalline structure with a crystallite size of (2-5) nm.

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STRUCTURE AND RESIDUAL STRESSES IN NiCoFeCrMn AND NiCoFeCr HEAS IRRADIATED WITH HELIUM IONS

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Modern challenges facing the scientific and technological part of nuclear power are associated to a large extent with increasing the efficiency of nuclear power plants by increasing their operating temperatures [1]. Materials for the core and protection of reactors must withstand temperatures up to 500-850°C [2]. Moreover, such reactors will experience high-dose neutron irradiation. Structural materials must withstand radiation loads up to 100 dpa (displacements per atom) [3], and according to other sources - up to 400-600 dpa (equivalent to 80 years of reactor operation) [4]. One of the most promising classes of materials for solving such problems are high-entropy alloys (HEA) [5-6]. They attract the attention of scientists from all over the world, and the works of the Cantor, Senkov, Yeh teams are recognized as pioneers in this field [7-8].

The structure and composition of NiCoFeCr and NiCoFeCrMn HEAs formed by arc melting and irradiated with low-energy 40 keV He^{2+} ions and a fluence of 2×10^{17} cm^{-2} have been studied. Bulk alloys based on single-phase solid solutions (Ni,Co,Fe,Cr) and (Ni,Co,Fe,Cr,Mn) with an fcc lattice, a coarse-grained structure (80–100 μm) and a uniform distribution of elements over depth were manufactured. In NiCoFeCr and NiCoFeCrMn alloys, tensile macro- (103±10 and 44±5 MPa) and microstresses (1.05±0.15 and 0.88±0.15 GPa) were revealed, the emergence of which is associated with mechanical processing of materials at the manufacturing stage.

It was found that the irradiation of NiCoFeCr and NiCoFeCrMn HEAs by He^{2+} ions with the energy 40 keV at a fluence of up to 2×10^{17} cm^{-2} does not lead to a change in the elemental and phase composition, as well as to erosion of the sample surface. It was re-vealed that irradiation of NiCoFeCr and NiCoFeCrMn HEAs with helium ions with a fluence of 5×10^{16} cm^{-2} leads to the formation of compressive stresses (-90...-160 MPa) and their growth over -650 MPa with an increase in fluence up to 2×10^{17} cm^{-2}. The greatest increase in the stress level was revealed for the region of maximum damage dose and helium implantation.

Irradiation with He^{2+} ions also leads to an increase in the level of compressive microstresses up to 2.7 GPa at a fluence of 5×10^{16} cm^{-2} and up to 6.8 at 2×10^{17} cm^{-2}. An in-crease in the dislocation density by a factor of 5-12 for a fluence of 5×10^{16} cm^{-2} and by 30-60 for a fluence of 2×10^{17} cm^{-2} was also revealed. The greatest changes in stresses and dislocation density are established for the region of maximum damage dose and con-centration of implanted helium.

It has been determined that HEAs of NiCoFeCrMn are characterized by a higher level of macro- and microstresses, dislocation density, as well as a larger increase in their values with increasing helium ion fluence compared to NiCoFeCr. It has been established that NiCoFeCrMn HEAs are characterized by higher radiation resistance compared to the NiCoFeCr alloy.

The work was carried out with the financial support of the Russian Federation, represented by the Ministry of Science and Higher Education (project No. 075-15-2021-1348) within the framework of event No. 3.1.14.

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