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MODERN METHODS OF VACUUM ARC IGNITION IN TECHNOLOGICAL PLASMA SOURCES

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The study investigates various methods of initiating vacuum-arc discharges in technological plasma sources. New designs of plasma sources have been developed, in which vacuum arc ignition is carried out using both contact and non-contact methods, including the use of a starting injector, the transition from a glow discharge to an arc discharge, and laser radiation with cleaning of the laser beam input window from the condensed film. It was found that the service life of starting injectors depends on the material filling the discharge gap: with M-7 ceramic it does not exceed 10^4 operations, with 22KhS ceramic it is about 10^5 operations, and when using composite materials it exceeds 10^6 operations under the conditions of an ignition energy of 5 J, a working pulse frequency of 1 Hz, and an arc duration of 2 s.

INTRODUCTION

Plasma flows generated by cathode spots of the vacuum-arc discharge have found wide practical application in the deposition of vacuum-arc coatings for various purposes, characterized by high performance properties [1, 2]. The fields of application of such coatings are diverse and include aerospace engineering, mechanical engineering, nuclear power, etc.

The reliable operation of technological plasma sources that generate these plasma flows directly depends on how the problem of vacuum arc initiation is solved in each specific case. Neglecting this issue in the early stages of vacuum-arc technology development, according to I.I. Aksyonov, delayed the advancement and automation of several vacuum-arc technological processes for years [3].

The aim of this work is to study methods for improving the efficiency of ignition systems of vacuum-arc discharges in plasma sources. Solving this issue will lead to improved technical characteristics of plasma sources and, consequently, enhance the quality of the coatings produced with their help.

1. ANALYSIS OF THE CURRENT STATE OF INCREASING THE IGNITION SYSTEMS EFFICIENCY

The excitation of a vacuum arc discharge, in general, occurs through the formation of a "plasma bridge" between the cathode and anode. Possible methods of vacuum arc excitation were considered by I.G. Kesayev [4]. The specific features of vacuum arc initiation in technological plasma sources are discussed in works [2, 3, 5].

The analysis of currently developed ignition systems for vacuum-arc discharge reveals the following directions for improving their efficiency [5]:

– development of new design solutions for both individual components and the ignition system as a whole;

– use of composite materials to fill discharge gaps in starting devices;

– creation of new circuit design solutions for ignition system power supplies;

– application of "non-traditional" methods of vacuum-arc discharge ignition, such as transitioning from a glow discharge to an arc discharge, and the use of laser radiation for arc initiation.

The application of design solutions typically involves changes in both the shape and arrangement of components of vacuum arc ignition system, as well as the addition of extra elements [6, 7]. The use of new materials in the triggering discharge gaps reduces surface breakdown voltage and improves the reliability of ignition system operation with such materials [8, 9]. New circuit design solutions for the ignition system power supply units further enhance the reliability of their operation [10, 11].

A promising direction of vacuum arc excitation, especially in the pulsed plasma sources, is the use of "non-traditional" ignition methods: transition from a glow discharge to an arc discharge [3, 12, 13] and arc initiation using laser radiation [14–16]. Referring to these methods as non-traditional implies that, although they are well-known [4], they have not yet found wide practical application in the designs of vacuum-arc plasma sources for various reasons.

In the case of using the glow-to-arc discharge transition, this is due to the fact that its practical implementation at low pressures is extremely difficult. Additionally, the gradual cleaning of the cathode surface from various inhomogeneities leads to a decrease in the reliability of vacuum arc initiation, which limits the technological capabilities of plasma sources with such an ignition system.

An almost unlimited service life, due to the absence of an igniting electrode and a dielectric insert in the arc ignition unit, can potentially be achieved by vacuum arc ignition systems using laser radiation. However, the unresolved problem of contamination of the laser beam input window into the vacuum chamber by cathode erosion products prevents achieving a long service life of ignition systems with this method of arc excitation. Attempts to solve this problem mechanically using shutters [14] or transparent plastic films that are continuously moved in front of the laser beam input window [15, 16] significantly complicate the design of the ignition system and are not optimal.

The analysis of the considered vacuum arc ignition systems, both in stationary and pulsed plasma sources, shows that practically every method of vacuum arc excitation has its own advantages and drawbacks [5].

2. RESEARCH RESULTS

To date, two main types of arc ignition systems have been studied to varying degrees – contact and non-contact.

In contact systems, the initial plasma cloud is generated by a discharge between the igniting electrode and the main cathode. This method was used in the designs of the first technological plasma sources developed by the Kharkiv Institute of Physics and Technology [1, 2] and is still applied in experimental research. However, its full potential has not yet been exhausted. To reduce the starting pulse voltage, the gap between the igniting electrode and the cathode is usually filled with ceramic or other materials.

In non-contact systems, there is no direct contact between the ignition components and the cathode. The starting plasma can be generated by an autonomous plasma injector, a glow discharge, or laser radiation.

2.1. CONTACT IGNITION SYSTEMS

The use of a spark discharge for igniting a vacuum arc in technological plasma devices has specific characteristics determined by the low voltage of arc discharge power supplies, the relatively large distances between the main electrodes, and the fact that the arc is excited on a cold cathode. The service life of the spark ignition device in such systems is often determined not so much by the parameters of the spark discharge itself, but rather by the influence of the arc discharge plasma and arc attachments on the ignition components.

Therefore, when selecting the design of the cathode-ignition assembly, it is necessary to consider not only the conditions for initiating the cathode spot but also the requirements for protecting the ignition elements from the effects of the main arc discharge – for example, by directing the cathode spot away from the ignition site toward the working surface of the cathode.

The simplicity of this ignition method and the ease of its implementation explain the frequent attempts to apply it in various plasma devices. Consequently, experimental data on the ignition performance and lifetime characteristics of devices employing auxiliary spark discharge for initiating vacuum-arc discharge are of certain practical interest.

The design of the contact-type ignition devices studied in this work is shown in Fig. 1.

As a result of the tests, it was proven that with an arc ignition probability of no more than 60%, the service life of ignition devices designed according to Fig. 1,a-b does not exceed several thousand operations due to the intensive erosion of the ignition elements, primarily as a result of the active impact from the cathode spot of the main arc discharge.

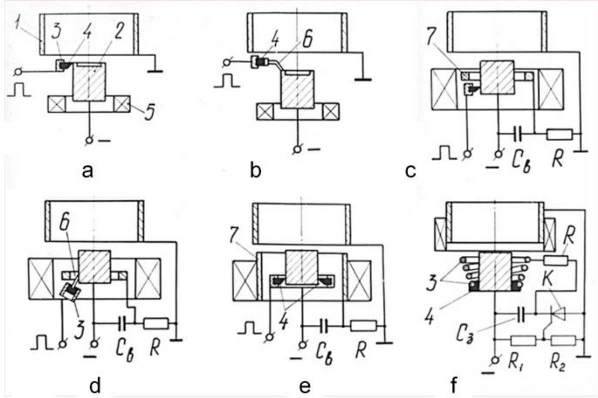

Fig. 1. Spark ignition devices of the contact type: 1 – anode; 2 – cathode; 3 – igniting electrode; 4 – dielectric insert; 5 – solenoid; 6 – "bird's beak"; 7 – auxiliary anode

A vacuum-arc device, the schematic of which is shown in Fig. 1,f [17, 18], is of practical interest. In this device, the igniting electrode and auxiliary anode are designed as a single structural element in the form of a truncated cone-shaped spiral. These design features, firstly, do not prevent the condensation of metal vaporized by the cathode spot of the arc onto the surface of the triggering discharge gap during operation, and secondly, significantly facilitate the movement of the cathode spot from the initiation point to the working end of the cathode. In this case, the magnetic field responsible for driving the cathode spot is generated by the current of the triggering discharge itself flowing through the turns of the cone-shaped spiral. This ignition system does not require a separate power supply and operates in automatic mode from the arc power source. This mode is ensured by the appropriately connected thyristor K, voltage dividers R_1, R_2, and blocking capacitor C_b. For reliable arc discharge excitation in the plasma source, it is necessary that during its operation the metallic film on the dielectric surface, destroyed during the ignition process, has time to recover. Later, this method of arc initiation became known in English-language literature as "triggerless triggering of vacuum arcs" [19].

2.2. PULSED PLASMA SOURCE WITH CONTACT IGNITION SYSTEM FOR THE DEPOSITION OF MULTICOMPONENT COATINGS

To generate multi-element vacuum-arc coatings, it is necessary to produce a multicomponent plasma from which their condensation takes place. For this purpose, a pulsed plasma source with a composite cathode was developed, as shown in Fig. 2. The external view of the composite cathode assembly is presented in Fig. 3. The designations are the same as in Fig. 2. The circles limiting the erosion zone of the cathode base material are marked with dotted lines. A preliminary version of such a plasma source is described in [20, 21].

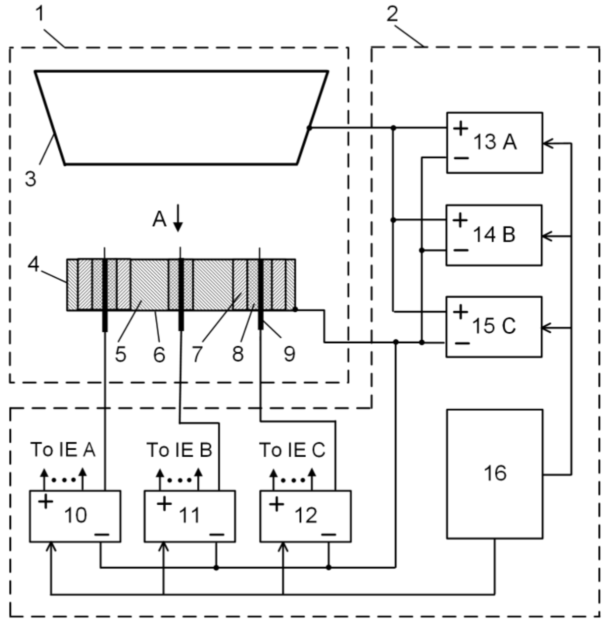

Fig. 2. Pulsed vacuum-arc plasma source with the composite cathode assembly:
1 – plasma source schematic; 2 – power supply circuit; 3 – anode; 4 – cathode assembly; 5 – base of the cathode assembly; 6 – cooled end surface of the composite cathode; 7 – cylindrical inserts made of metals that form the coating composition; 8 – insulator; 9 – igniting electrode; 10–12 – igniting units; 13–15 – vacuum arc power supply units; 16 – control unit

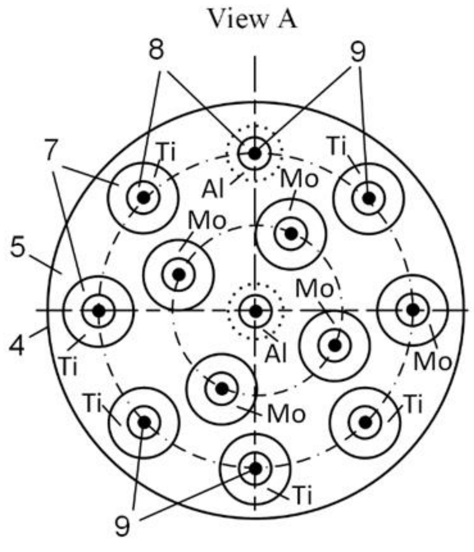

Fig. 3. External view of the composite cathode assembly with Ti and Mo inserts

The composite cathode assembly of this plasma source includes a base made of a metal with high thermal conductivity (e.g., aluminum), shaped as a cylinder with end surfaces, one of which is cooled. Through-holes are made in the cathode base, uniformly distributed along concentric circles relative to the axis of the base. Cylindrical inserts made of metals that form the coating composition are vacuum-tightly mounted into these holes. Inside each insert, an insulator with an igniting electrode is tightly fitted. In cases where the base material is part of the coating composition, instead of at least one insert hole, openings are made in the cylindrical base into which insulators with igniting electrodes are vacuum-tightly mounted.

Practical tests of the developed plasma source in coating deposition mode – with an arc current amplitude of 420 A, arc pulse durations of 50 μs for titanium, 45 μs for molybdenum, and 665 μs for aluminum, at various pulse frequencies – showed that the resulting multicomponent coatings have a composition close to the specified one, and the pulsed plasma source demonstrates reliable performance.

2.3. NON-CONTACT IGNITION SYSTEMS

A more advanced method compared to the previously discussed contact ignition is the non-contact arc excitation technique using a plasma injector, proposed by I.I. Aksyonov and V.A. Bilous [22]. This method is characterized by high enough response speed, compactness, reduced destructive impact on the ignition components of the vacuum-arc discharge, and improved manufacturability due to the elimination of the need to adjust and fix the ignition system components each time the cathode wears out or is replaced. This arc initiation system was first implemented as a standard feature in the plasma sources of “Bulat-6” installations and was later used in subsequent modifications of this equipment series.

An unquestionable advantage of such an ignition system is the possibility of using the starting injector as a separate, standardized ignition “spark plug” [8]. To assess the reliability and service life of the first ignition stage – the starting injector – various designs of these injectors (shown in Fig. 4,a–f) were studied with different materials used to fill their discharge gaps.

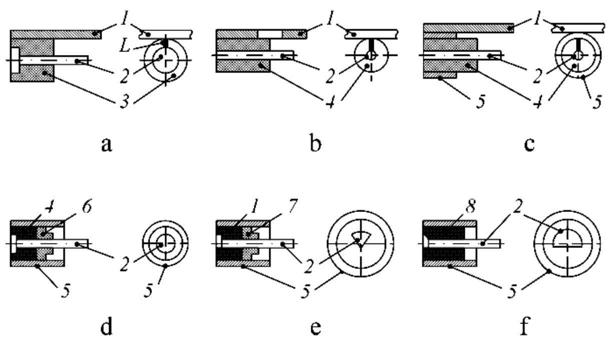

Fig. 4. Variants of starting injector designs:
1 – auxiliary anode; 2 – igniting electrode; 3 – 22KhS ceramic; 4 – M-7 ceramic; 5 – external electrode of the starting injector; 6 – electrically conductive composite material [23]; 7 – ceramic ring; 8 – composite material [24]

It was found that the service life of starting injectors, when the discharge gap is filled with M-7 ceramic, does not exceed 10^4 operations; with 22KhS ceramic – around 10^5 operations; and when using composite materials [23, 24], it exceeds 10^6 operations at an ignition energy of 5 J, operating pulse frequency of 1 Hz, and arc duration of 2 s.

The starting characteristics of the plasma source of the “Bulat-6” installation using an injector made from composite material [24] are shown in Fig. 5.

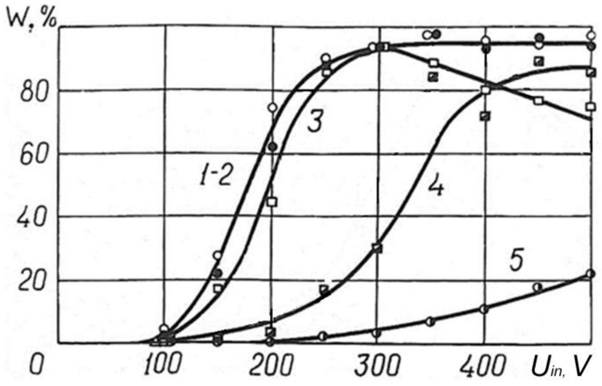

Fig. 5. Influence of the ignition pulse energy on the starting characteristics of the standard plasma source of the "Bulat-6" installation:
cathode – Ti; I_d = 320 A; U_{oc}^c = 65 V; p = 1.3·10⁻³ Pa;
H_{dc} = 1.6·10⁴ A/m; H_f = 0; 1 – C_{st} = 20 μF;
2 – C_{st} = 80 μF; 3 – C_{st} = 40 μF; 4 – C_{st} = 20 μF;
5 – C_{st} = 10 μF

The increased service life of starting injectors made of composite materials is attributed to their higher resistance to electrical discharge. The reliability of ignition devices made of composite materials is also enhanced due to their ability to operate in the absence of a metallic film in the discharge gap, owing to their low surface breakdown voltage (up to 100…200 V/mm).

2.4. NON-TRADITIONAL METHODS OF VACUUM-ARC DISCHARGE EXCITATION

2.4.1. Vacuum arc excitation via glow-to-arc discharge transition

The interest in initiating technological plasma sources through the transition of various types of glow discharge into a vacuum arc discharge was driven by the fact that, in this case, the starting plasma can be generated by an electrode system of relatively large dimensions. Moreover, manufacturing these electrodes as massive and potentially water-cooled components significantly increases the system resistance to the destructive effects of the arc discharge, which is particularly important in pulsed operating modes.

The first studies aimed at determining the feasibility of using glow discharge for initiating vacuum arcs in technological plasma sources were carried out at the Kharkiv Institute of Physics and Technology in the 1980s. The research was conducted in the following directions: glow discharge in a Penning-type electrode system [12], and glow discharge using a hollow cathode with dielectric stimulators of cathode spots [13, 25].

The results of research in the first direction demonstrated the following: the use of a plasma source with such arc initiation is appropriate for technological processes that involve reactive gases forming compounds with the cathode material on its surface. The resulting films act as active centers where cathode spots are formed. Otherwise, after several hundred operations, the probability of glow discharge initiation decreases to 10…50%, which is attributed to the cleaning of the cathode surface from various inhomogeneities.

The technological capabilities were successfully expanded in a plasma source where glow-to-arc discharge transition is carried out in a hollow cathode system using dielectric cathode spot stimulators. An experimental prototype of a plasma source, in which the arc is initiated by the transition from glow to arc discharge with dielectric cathode spot stimulators, along with their starting characteristics, are shown in Figs. 6 and 7, respectively.

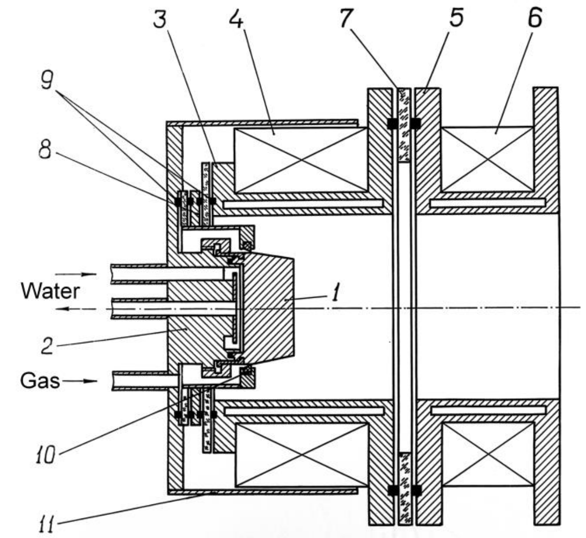

Fig. 6. Experimental prototype of a plasma source with dielectric cathode spot stimulators:
1 – cathode; 2 – cathode holder; 3 – anode; 4, 6 – coils;
5 – igniting electrode; 7 – insulator; 8 – shield;
9 – seals; 10 – M-7 ceramic; 11 – casing

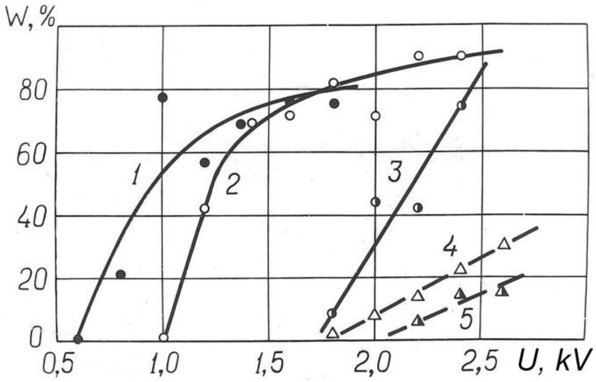

Fig. 7. Starting characteristics of the plasma source with dielectric cathode spot stimulators:
H_1 = 1.6·10⁴ A/m; 1–3 – opposing connection,
4, 5 – series connection of coils 4 and 6;
1, 4 – H_2 = 8·10³ A/m; 2, 5 – H_2 = 1.6·10⁴ A/m;
3 – H_2 = 6.4·10⁴ A/m

The results of studies on a plasma source with arc ignition using the glow-to-arc discharge transition with dielectric cathode spot stimulators show that the arc discharge is reliably initiated within a wide pressure range (approximately from 10^{-2} to 10 Pa) by voltage pulses of about 2 kV in the presence of a magnetic field with an intensity of 5.6·10⁴ A/m, at a starting pulse energy of approximately 2 J. The presence of dielectric cathode spot stimulators ensures the operability of the device in environments with both reactive and inert gases.

Maximum reliability of vacuum arc excitation in a technological plasma source can be achieved using a combined-type ignition system, where the first two stages are the same as in the standard plasma sources of the "Bulat-6" installations, and the operation of the third ignition stage is based on the transition from glow to arc discharge [26]. During the ion cleaning mode, the first two ignition stages are used, while in the coating deposition mode, the second and third stages are employed.

2.4.2. Solving the issue of input window contamination during arc initiating with a laser beam

The solutions used in works [14–16] for protecting the laser radiation input window from contamination during arc initiation by a laser beam are not optimal, as they significantly complicate the design of the ignition system and the plasma source itself. This increases its cost and considerably reduces reliability. Moreover, the measures proposed to minimize window contamination [14] still require periodic cleaning or replacement of the laser input window.

A method was proposed to address the issue of laser input window contamination in pulsed vacuum-arc plasma sources with laser arc ignition. This method is implemented in a device shown in Fig. 8 [27].

The method consists in periodically delivering energy via a defocused laser beam into the layer of condensate formed on the surface of the laser radiation input window. The focal point of this cleaning laser beam is located outside the vacuum chamber, which ensures the absence of unintentional triggering of the plasma source. Additionally, the optical axis is perpendicular to the surface of the input window, providing optimal conditions for removing the formed condensate film.

The periodicity of cleaning the laser radiation input window, which determines the transmission capacity of the window, is calculated by the control unit (16). This unit receives information about the vacuum chamber pressure p, the cathode material m, the required number of pulses from the pulsed plasma source (vacuum-arc discharge impulses) n1, and the number of pulses already executed during the current technological process n2.

In addition, the defocused spot area S_{def} of the cleaning laser beam on the surface of the laser radiation input window facing the cathode of the plasma source is determined under the condition that the power density q of the laser radiation on the cleaned surface lies within the range $10^4 \le q \le 10^5$ W/cm². Furthermore, the condition $S_{def} \ge S_{init}$ must be satisfied, where S_{init} is the spot area of the initiating laser radiation on the surface of the input window facing the cathode of the plasma source.

Initiation of the vacuum arc in a pulsed plasma source using the proposed method, which enables the removal of the condensate layer from the laser radiation input window, is characterized by a stable arc ignition probability of 95% at an arc pulse frequency of 300 Hz, regardless of the plasma source operating time.

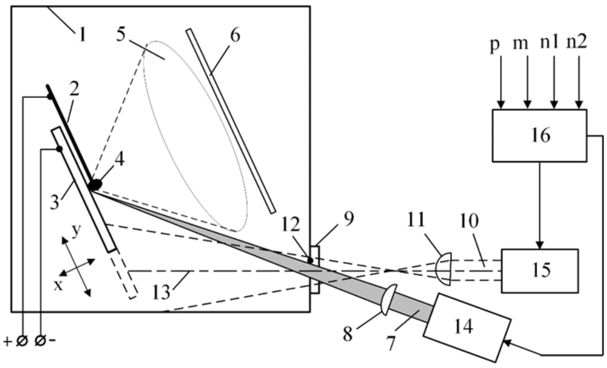

Fig. 8. Schematic of the pulsed plasma source with a laser-based ignition system:
1 – vacuum chamber; 2 – anode; 3 – movable cathode; 4 – cathode spot of the vacuum arc; 5 – plasma cloud generated by the cathode spot; 6 – substrate; 7 – laser beam that initiates the vacuum arc; 8 – optical system that focuses the initiating laser beam on the cathode; 9 – laser radiation input window; 10 – auxiliary laser beam; 11 – optical system that defocuses the auxiliary laser beam; 12 – side of the input window where cathode material condenses; 13 – optical axis of the auxiliary laser beam; 14 – main laser;
15 – auxiliary laser; 16 – control unit

CONCLUSIONS

The results obtained in this work can be summarized as follows:

The analysis of currently developed vacuum-arc discharge ignition systems has revealed the following directions for improving their efficiency: development of new design solutions for both individual components and the ignition system as a whole;

use of composite materials to fill the discharge gaps of ignition devices; application of "non-traditional" methods for initiating vacuum-arc discharge, such as transition from a glow discharge to an arc discharge; and the use of laser radiation for arc ignition.

Based on the conducted research, designs of vacuum-arc plasma sources with contact-type ignition systems have been developed that ensure a sufficiently high performance. The most efficient design proved to be the ignition system configuration in which the igniting electrode and auxiliary anode are implemented as a single structural element in the form of a truncated cone-shaped spiral. This type of ignition system does not require a separate power supply unit and can operate automatically from the arc power source.

For the implementation of a non-contact arc excitation method using a plasma injector, various injector designs were studied, with different materials used to fill their discharge gaps. It was found that the service life of the starting injectors, when the discharge gap is filled with M-7 ceramic, does not exceed 10^4 operations; with 22KhS ceramic, the service life reaches about 10^5 operations; and when composite materials are used, it exceeds 10^6 operations under ignition energy of 5 J, working pulse frequency of 1 Hz, and arc duration of 2 s.

Arc ignition with the glow-to-arc discharge transition using dielectric cathode spot stimulators extends the operational capabilities of the plasma source. In this case, the arc discharge is stably initiated over a wide pressure range (from 10^{-2} to 10 Pa) using voltage pulses of approximately 2 kV in the presence of a magnetic field with an intensity of $5.6 \cdot 10^4$ A/m, at a starting energy of about 2 J. The presence of dielectric cathode spot stimulators ensures the operability of the ignition system in both reactive and inert gas environments. A plasma source design with a combined vacuum arc ignition system has been developed, providing maximum reliability of arc excitation.

A method has been proposed to solve the issue of the laser beam input window contamination in pulsed vacuum-arc plasma sources with laser arc ignition. The method is implemented by a specially designed device. It consists in periodically delivering energy via a defocused laser beam into the condensate layer formed on the surface of the laser radiation input window, which allows the condensate to be effectively removed.

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СУЧАСНІ МЕТОДИ ЗАПАЛЮВАННЯ ВАКУУМНО-ДУГОВОГО РОЗРЯДУ В ТЕХНОЛОГІЧНИХ ДЖЕРЕЛАХ ПЛАЗМИ

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Виконано дослідження різних методів запалювання вакуумно-дугового розряду в технологічних джерелах плазми. Розроблено нові конструкції джерел плазми, в яких запалювання вакуумної дуги здійснюється як контактним методом, так і безконтактними, із застосуванням пускового інжектора, переходу тліючого розряду в дуговий і лазерним випромінюванням (ЛВ) з очищенням вікна введення ЛВ від плівки, що конденсується. Виявлено, що ресурс пускових інжекторів при заповненні розрядного проміжку керамікою М-7 не перевищує 10^4 спрацьовувань, керамікою 22ХС – на рівні 10^5 спрацьовувань, а при застосуванні композиційних матеріалів – перевищує 10^6 спрацьовувань при енергії підпалювання 5 Дж, частоті робочих імпульсів 1 Гц і тривалості дуги 2 с.