https://doi.org/10.46813/2023-147-152

UDC 621.793.7

LONG-LIFE PULSED VACUUM-ARC PLASMA SOURCE

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The design of a pulsed vacuum-arc plasma source with an ignition system based on dielectric surface breakdown is presented and the principle of its operation is described. In the engineered plasma source, a four-section anode is used along with an equal number of arc ignition sections. Additionally, separate power supply circuits are employed for both the main pulsed arc discharge and the arc ignition circuit. Independent operation of each section of this device is carried out, essentially constituting a combination of four pulsed plasma sources in one, the coordinated functioning of which is ensured by the control system. Practical tests of the pulsed plasma source have revealed its advantages as followed: a fourfold increase in the ignition system life-time; achieving uniform depletion of the cathode working surface; and, under specific conditions, enhancing the productivity of the plasma source.

INTRODUCTION

Vacuum-arc plasma sources, being among the key devices in plants for ion-plasma treatment of products, greatly influence the efficiency of processes and the quality of the surface layer [1, 2]. The reliability and durability of such sources depend on how the issue of vacuum arc excitation is solved in each specific case. Disregarding these matters for years has hindered the development of numerous ion-plasma technological processes and their automation [3].

The work on replacing the initial mechanical ignition systems of vacuum-arc discharge in technological plasma sources, which were inert and unreliable, was initiated in the mid-1970s of the last century at the Kharkiv Institute of Physics and Technology [3, 4]. This led to the development of fairly reliable plasma ignition systems (with a resource close to 10^6 ignitions) for plasma sources operating in a steady-state mode. However, the problem of creating arc discharge ignition systems that ensure reliable operation of pulsed plasma sources with a resource exceeding 10^6 ignitions, which is necessary for the implementation of certain promising technological processes, remained unresolved.

Recently, pulsed vacuum-arc plasma sources have gained widespread use, which provide a smaller number of microparticles in the generated plasma flow, and consequently, higher coating quality (especially for optical and microelectronics coatings), compared to stationary plasma sources. They do not ensure complete absence of microparticles in the plasma, but they are much simpler and cheaper compared to methods using plasma filters [5]. For pulsed vacuum-arc plasma sources, the question of arc excitation is particularly acute, as their arc excitation system resource must be several orders of magnitude higher than in stationary plasma sources.

1. CURRENT STATE OF THE ISSUE

The analysis of currently developed ignition systems for vacuum-arc discharge, both in stationary and pulsed plasma sources, is represented in [6] revealing the following directions for improving their efficiency:

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

– creation of new composite materials and their utilization for filling the discharge gaps of starting devices;

– design of novel circuit solutions for the power supply sources of starting discharges;

– utilization of unconventional ignition methods for vacuum-arc discharge, including the transition from a glow discharge to an arc one and employing laser radiation for arc ignition.

When applying design solutions, both the shape and the arrangement of elements of vacuum arc ignition systems are typically modified and additional components are introduced [7–9]. The use of new materials in starting discharge gaps reduces the surface breakdown voltage and enhances the reliability of ignition systems utilizing such materials [10, 11]. Novel circuit solutions for the power supply sources of starting devices allow for further improvement in their reliability [12–14].

An innovative direction for vacuum-arc excitation, especially in pulsed plasma sources, involves the utilization of unconventional excitation methods: the transition from a glow discharge to an arc one [3, 15–17] and the arc initiation using laser radiation [18–20]. When discussing the unconventional nature of these vacuum-arc excitation methods, it is implied that although they are fairly well-known, they have not found extensive practical application in vacuum-arc plasma source designs due to specific reasons.

In the case of applying the method of transition from a glow discharge to an arc one, this is associated with the fact that using such plasma sources is reasonable only in technological processes involving reactive gases that form compounds with the cathode material on its surface. The created films serve as active centers where arc cathode spot formation occurs. In other cases, after several hundred ignitions, the probability of transition from a glow discharge to an arc one decreases to values of 10...50%, which can be attributed to the cleansing of the cathode surface from various irregularities and contaminants. Additionally, the effective arc occurrence during the transition from a glow discharge to an arc one in plasma sources is achieved at pressures not lower than 10^{-2} Pa limiting their technological capabilities.

Practically unlimited lifespan due to the absence of an igniting electrode and a dielectric insert in the arc excitation units potentially could be achieved by vacuum-arc ignition systems utilizing laser radiation. However, the lack of a solution to the issue of contamination of the laser beam input window inside the vacuum chamber with cathode erosion products prevents achieving a long life for ignition systems using this method of arc excitation. Attempts at mechanically addressing this problem using shutters [18] or transparent plastic films that are constantly moved in front of the laser radiation input window [19] significantly complicate the ignition systems design and are not perfect solutions.

The analysis of the considered vacuum-arc discharge ignition systems, both in stationary and pulsed plasma sources, reveals that practically every method of vacuum-arc ignition has its own advantages and disadvantages [6].

One of the most widespread ignition systems, due to its simplicity of implementation, fast operation, suitability for automated processes, a fairly high resource (over 10^6 ignitions), and stable operation under specific conditions, is the ignition system utilizing pulsed breakdown on the dielectric surface (so-called "contact" ignition systems [3, 6]). This pulsed breakdown creates an initial plasma that subsequently initiates the main vacuum-arc discharge. Typically, the dielectric surface is coated with a thin conductive film that is continuously restored from cathode erosion products during the operation of the plasma source. The presence of such a self-renewing film significantly reduces the breakdown voltage of this ignition system (essentially, instead of dielectric surface breakdown, an electric explosion of this film occurs) and allows the ignition system to be powered directly from the arc power supply source [21]. In pulse mode, such an ignition system can operate automatically [22]. Its main limitation, which restricts its application in pulsed plasma sources, is the relatively low operational lifespan.

The aim of the study is to develop a pulsed vacuum-arc plasma source with an extended operational lifespan of the arc ignition system using pulsed breakdown on the dielectric surface, along with its high productivity.

2. DESIGN OF THE PULSED PLASMA SOURCE

Schematically, the design of the developed pulsed vacuum-arc plasma source with its power supply circuits is shown in Fig. 1. View of the cathode from the side of the substrate holder is shown in Fig. 2.

The pulsed vacuum-arc plasma source contains a coaxially arranged sectional tubular cone-shaped anode made of stainless steel, divided into sections 1.1, 1.2, 1.3, and 1.4 (see shown schematically in Fig. 1), which are electrically isolated from each other, and a consumable disc cathode made of titanium 2, positioned on one side of the anode (toward the smaller base of the anode). On the other side of the anode sections 1.1, 1.2, 1.3, and 1.4, there is a holder for the substrate 3 with processed products 4.

Plasma source power supply is provided from the power supply source 5, where its positive terminal is connected to the first terminals of storage capacitors C_1, C_2, C_3, C_4, and through switching elements S_1, S_2, S_3, S_4 to the corresponding anode section, while the negative terminal is connected to the second terminals of storage capacitors C_1, C_2, C_3, C_4, and to the cathode 2.

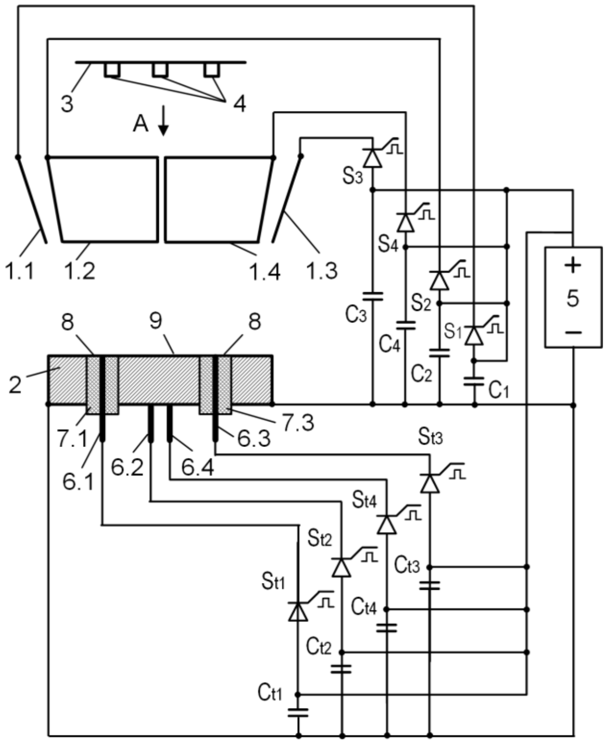

Fig. 1. Design of the combined pulsed vacuum-arc plasma generator:
1.1–1.4 – anode sections; 2 – cathode; 3 – holder for the substrate with products 4; 5 – power supply source; 6.1–6.4 – igniting electrode sections; 7.1–7.4 – dielectric spigots; 8 – conductive film; 9 – cathode working surface; S_1–S_4 – switching elements in the vacuum-arc circuit; C_1–C_4 – storage capacitors in the vacuum-arc circuit; S_{t1}–S_{t2} – switching elements in the vacuum-arc ignition circuit; C_{t1}–C_{t2} – storage capacitors in the vacuum-arc ignition circuit

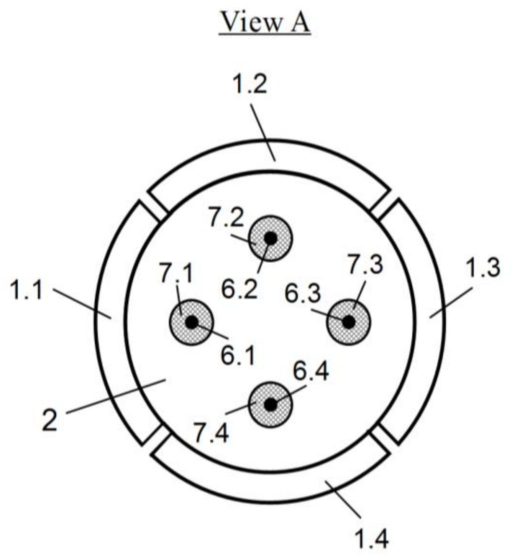

Fig. 2. View of the cathode from the side of holder for the substrate.
The designations are the same as in Fig. 1

The cathode 2 uniformly incorporates sections of igniting electrode (see their number is equal to the number of anode sections, Fig. 2), formed by electrodes 6.1, 6.2, 6.3, 6.4, located inside insulators (dielectric spigots) 7.1, 7.2, 7.3, 7.4 of these sections. Insulators 7.1, 7.2, 7.3, 7.4 of each section of the igniting electrode are tightly positioned within the cathode 2, and their working surface 8 is aligned with the working surface of the cathode 9. The electrode outputs of each igniting electrode section 6.1, 6.2, 6.3, 6.4 are positioned on the cathode side opposite to the anode and are connected to the first terminals of switching elements S_{t1}, S_{t2}, S_{t3}, S_{t4}. The second terminals of switching elements S_{t1}, S_{t2}, S_{t3}, S_{t4} are connected to the first terminals of additional storage capacitors C_{t1}, C_{t2}, C_{t3}, C_{t4}, and the positive terminal of the power supply source 5, which negative terminal is connected to the second terminals of additional storage capacitors and to the cathode 2.

3. PRINCIPLES OF OPERATION OF THE PULSED PLASMA SOURCE

Designing a tubular anode in a sectional manner, considering that the tube can have a cylindrical, rectangular, conical, or other shape, allows achieving the following objectives. When the igniting electrode section, located near the corresponding anode section, is triggered from previously applying voltage through the switching element from a storage capacitor charged by the power source, it leads to the occurrence of a pulsed vacuum-arc discharge between the cathode and the corresponding anode section. In this case, since the other anode sections are disconnected from their storage capacitors (their switching elements are turned off), and the anode sections are not electrically connected to each other, the pulsed vacuum-arc discharge will exist only between the cathode and corresponding anode section. The plasma created by this discharge (its cathode spots) will pass through the anode hole onto the substrate with the processed products.

After the discharge in the considered anode section ceases due to the discharge of its storage capacitor the sequential activation of each other anode section occurs in the same manner. At the same time, the sequence of section activation is not important; what matters is that all sections of the pulsed plasma generator will be triggered in one cycle, and then the cycle is repeated.

The subsequent activation of each consecutive section can be carried out immediately after the electric strength restoration of the cathode-anode gap of the plasma source (deionization of the plasma created by the previous section of the proposed pulsed vacuum-arc plasma source). This delay between device sections activations is necessary to prevent the occurrence of cathode spots of the next vacuum-arc discharge outside the area of activation of the successive section of the igniting electrode. It would result in uneven erosion (depletion) of the cathode working surface. Such cathode spots occurrence in the absence of a delay between device sections activation can happen due to incomplete deionization of the plasma after the termination of the arc discharge in the previous section of the device, as well as due to insufficient cooling of the area where the cathode spot was last located.

The electric strength recovery time of the cathode-anode gap after a vacuum-arc discharge for various electrode materials, distances between electrodes(a few millimeters), and applied voltages (several tens of kilovolts) was studied in several works referenced in [23], and it amounted to values on the order of 1…10 μs. In our case, the distance between the anode and the cathode is several orders of magnitude higher and the voltage between them does not exceed 1000 V, so it can be assumed that the complete recovery of electric strength between the anode and the cathode occurs within a time period that does not exceed a fraction of a microsecond – one microsecond. Therefore, vacuum arc pulses in such a plasma source can follow one another within a very short time interval. This is also possible because of the fact that under other equal conditions, the storage capacitor in each anode section, which discharges after its activation, has a longer charging time due to the time until other anode sections will activate.

For stable operation of the ignition system in the proposed device, a balance is required between the amount of cathode material deposited on the surface of the dielectric spigot of each section of the igniting electrode during the passage of pulsed vacuum-arc discharges in the device, and the amount of material consumed from the surface of this spigot during the formation of the starting discharge between consecutive activations of the corresponding igniting electrode section. The film formation rate for chromium and titanium cathodes under conditions similar to ours was studied in [24]. If compared with the case of a solid anode and, accordingly, only one igniting electrode section, and conditions are created for the equality of the amount of material that reaches the dielectric spigot and is carried away from it during its activation, then in our case, for four sections of the anode and the igniting electrode, to achieve the same conditions under other equal circumstances, it is necessary either to reduce the current magnitude in the vacuum-arc pulse during its passage through each individual section, or to reduce its duration by four times. It is also possible to decrease both the current magnitude and the duration in such a way that the total charge transferred in the section per pulse is four times smaller.

Reducing the current magnitude in the pulsed vacuum-arc discharge is not advisable as it leads to a decrease in the device productivity. In contrast, reducing the duration of the arc pulses to the microsecond range allows leveraging all the advantages of the pulsed operation mode thus, reducing the number of microparticles in the generated plasma flow.

During operation, the cyclic activation of the pulsed plasma generator sections leads to the formation of cathode spots of the arc discharge. These spots undergo chaotic movement across the cathode surface throughout the existence of the pulsed discharge, causing erosive depletion of the cathode. This cathode depletion is predominantly carried out in circles centered around the individual centers of the igniting electrode sections.

In the general case, the number of igniting electrode sections is determined by the cathode diameter and the duration of the pulsed vacuum-arc discharges. The duration of the pulsed discharges is defined by the circle radius R around each igniting electrode section, where cathode erosive depletion primarily occurs. This radius in the case of the chaotic motion of the cathode spot is determined as the maximum possible value of its displacement x over the time interval of the pulsed discharge t. The time estimation it takes for the cathode spot to traverse the entire cathode surface with a radius of 0.03 m gives a value range of $10^{-2}…10^{-1}$ s [25]. Thus, with such a duration of vacuum-arc discharges, uniform depletion of the cathode working surface will be achieved. In our case, with four sections of arc discharge ignition uniformly distributed on the cathode surface, this duration can be reduced by a factor of four, and with a smaller cathode diameter, even further, without deteriorating the conditions for uniform depletion of the cathode working surface.

In the developed device, the resource of the ignition system is extended by a factor of N, where N is the number of arc ignition units (in our case, N = 4); furthermore, the sequential operation of the arc excitation system units contributes to enhancing reliability of arc ignition. This is because the conditions for forming a conductive film on the working surface of the dielectric spigot, which is a necessary component for arc excitation, are improved leading to reduced thermal load on the sections of the igniting electrode.

4. RESULTS OF PULSED PLASMA SOURCE TESTS

The results of testing the developed device were obtained as follows. The power supply source 5 (the SF134-1 power supply unit from the "Quant-15" installation was used as a power source) was turned on, which charged the storage capacitors C_1, C_2, C_3, C_4 (capacitors К75-40b-1600 V-100x3 μF ± 10%) and additional storage capacitors C_{t1}, C_{t2}, C_{t3}, C_{t4} (capacitors К75-40a-1600 V-4 μF ± 10%) up to a voltage of 1000 V.

After the charging of all capacitors (charging time less than 5 ms), the switching element S_1 (thyristors of ТБИ 343-500-12 type were used as switching elements S_1, S_2, S_3, S_4) was turned on by applying a pulse to the control electrode of the thyristor S_1 from the control system (see the control system is not shown in Fig. 1), which resulted in the voltage from the storage capacitor C_1 being supplied to the anode section 1.1. Simultaneously with the switching element S_1, the switching element S_{t1} (thyristors of ТБК-171-160-12 type were used as switching elements S_{t1}, S_{t2}, S_{t3}, S_{t4}) was turned on by applying a pulse to the control electrode of the thyristor S_{t1} from the control system. Activation of the switching element S_{t1} led to the application of voltage to the element 6.1 of the igniting electrode, which in turn triggered the electric explosion of the thin film located on the surface of the insulator 7.1 between the element 6.1 of the igniting electrode and the cathode 2. This conductive film was initially created by depositing a graphite layer on the surfaces of insulators 7.1, 7.2, 7.3, 7.4, and then, during the operation of the pulsed plasma source, it was formed by the cathode erosion products. The starting discharge that generated as a result of the thin film explosion initiated the main vacuum-arc discharge between the cathode 2 and the anode section 1.1 due to the discharge of the capacitor C_1. The plasma of this discharge, expanding and moving towards the holder of the substrate 3, formed a coating on the processed products 4.

After the operation of the first anode section of the device (termination of the vacuum-arc discharge in this section due to the discharge of capacitor C_1), one microsecond later (this time was guaranteed to ensure the restoration of electrical strength in the cathode-anode section gap of the plasma source), the switching elements S_2 and S_{t2} were simultaneously activated by applying pulses from the control system to their control electrodes. Similar to the first anode section, a pulsed vacuum-arc discharge occurred, but this time between the cathode and the second anode section. The plasma of this discharge also formed a coating on the processed products 4. It should be noted that the occurrence of the pulsed vacuum-arc discharge after the ignition system operation was carried out, as in [3, 6], with a delay, in our case on the order of 40 μs on average (the time required to reach the plasma density level of the starting discharge to the point where the initiation of the vacuum arc takes place).

Subsequently, after the activation of the second section of the pulsed vacuum-arc plasma source, the same procedure was repeated: the switching elements S_3 and S_{t3} were activated, ensuring the generation of a pulsed vacuum-arc discharge between the third anode section and the cathode. Similarly, after the third anode section of the plasma source had operated, the switching elements S_4 and S_{t4} were also activated, resulting in the initiation of a pulsed vacuum-arc discharge between the fourth anode section and the cathode.

The activation of the fourth anode section marked the completion of the device operational cycle. This cycle was then repeated for as long as necessary to achieve the desired coating thickness on the products 4.

In our case, the pulsed vacuum-arc plasma source was employed to obtain titanium nitride coatings on stainless steel samples in a series of five experiments. In each experiment, the device operated for 15 min, resulting in the formation of coatings approximately 1.7 μm thick on the samples. The operation mode of the plasma source was as follows: the amplitude of the vacuum arc discharge current was set at 380 A, the pulse repetition frequency was 260 Hz, with a pulse duration of 650 μs, and a delay time between vacuum arc pulses of about 3 ms. This delay consisted of the time required for the restoration of electrical strength in the cathode-anode gap after the vacuum-arc discharge, the time needed to form the starting discharge plasma of the necessary density for the excitation of the main vacuum-arc discharge (approximately 40 μs), and the arc pulses interval time to reduce the thermal load on the cathode unit.

The excitation system of the vacuum-arc discharge operated with a 97% arc excitation probability. Moreover, no irregularities were observed in the depletion of the cathode working surface.

To compare the productivity of the proposed pulsed plasma source with that of a stationary plasma source, on the "Bulat-6" installation, using the standard plasma source and an arc current of 80 A, titanium nitride coatings were obtained on the same samples at the same deposition time and the same distance from the anode cut. The average thickness of the coatings obtained on the samples was 2.7 µm. This indicates that the productivity of the developed pulsed plasma source is comparable to that of the stationary plasma source on the "Bulat-6" installation. Such high productivity of the proposed device is achieved due to the design of the pulsed plasma source, which combines four pulsed plasma sources into one, and their coordinated operation is ensured by the control system.

Testing the experimental device prototype at the mode with double pulse frequency of the vacuum arc (520 Hz, when the time interval between arc pulses was reduced) showed that after 4 min of operation, the cathode unit was overheated, resulting in the loss of device air tightness due to the failure of the cathode unit sealing gasket. This suggests that when operating the developed device at high-productivity modes equivalent to the productivity of stationary vacuum-arc plasma sources, it is necessary to provide cooling for its cathode unit. Thus, the design of the pulsed plasma source becomes more complex. However, its advantages are extended ignition system lifespan, relatively uniform depletion of the cathode working surface and high productivity. In addition to the mentioned advantages, the positive aspect, which involves retaining the benefits of pulsed plasma sources, gives every reason to believe that the developed combined pulsed vacuum-arc plasma source can be widely utilized in technological processes for obtaining vacuum-arc coatings of various functional purposes.

CONCLUSIONS

The pulsed vacuum-arc plasma source with the ignition system based on dielectric surface breakdown was investigated, its design was developed and the operation principle was described. Its practical tests showed that the design and circuit solutions applied in the device allow achieving the following results:

– extended ignition system lifespan by a factor of N, where N is the number of anode sections and ignition units of the vacuum-arc (in our case, N = 4, hence, increasing the lifespan by at least four times). Additionally, sequential operation of the arc excitation system contributes to increased ignition reliability, as conditions for forming a conductive film of cathode erosion products on the working surface of the dielectric spigot are improved, reducing the thermal load on the igniting electrode sections;

– uniform depletion of the cathode working surface, achieved by arranging the vacuum arc excitation units evenly on the cathode surface. In general, the number of the igniting electrode sections (units) is determined by the cathode diameter and the duration of pulsed vacuum-arc discharges, while the duration of pulsed discharges is defined by the radius of the circle around each igniting electrode section, where cathode erosive depletion occurs;

– increasing operational productivity of the plasma source to the level characteristic of stationary plasma sources, due to a significant increase in the ratio of pulsed vacuum-arc discharge duration (productive time) to the pulses interval time (auxiliary time). Such high productivity is facilitated by the design of the pulsed plasma source, which combines four pulsed plasma sources into one, and their coordinated operation is ensured by the control system.

ACKNOWLEDGEMENT

The authors would like to acknowledge financing of National Research Foundation of Ukraine under grant agreement No. 2020.02/0119.

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Article received 11.08.2023

ІМПУЛЬСНЕ ВАКУУМНО-ДУГОВЕ ДЖЕРЕЛО ПЛАЗМИ З ПІДВИЩЕНИМ РЕСУРСОМ РОБОТИ

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Наведено конструкцію і описано принцип дії імпульсного вакуумно-дугового джерела плазми з системою запалювання (СЗ) на основі пробою по поверхні діелектрика. У розробленому джерелі плазми завдяки використанню анода у вигляді чотирьох секцій і такої ж кількості секцій запалювання дуги, а також застосуванню розділених ланцюгів живлення як основного імпульсного дугового розряду, так і ланцюгів запалювання дуги, здійснюється незалежна робота кожної секції цього пристрою, що, по суті, є комбінацією чотирьох імпульсних джерел плазми в одному, узгоджена робота яких забезпечується системою керування (СК). Практичні випробування імпульсного джерела плазми показали такі його переваги: підвищення ресурсу СЗ у чотири рази; досягається рівномірне вироблення робочої поверхні катода і за певних умов забезпечується підвищення продуктивності роботи джерела плазми.