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Dual-Mode Pulsed Plasma Source

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This paper presents the design and operating principle of a newly developed dual-mode pulsed plasma source capable of operating either as a pulsed vacuum-arc plasma source or as a pulsed magnetron sputtering system. Switching between the two operating modes is achieved by changing the magnetic-field configuration within the plasma source, modifying the activation sequence of the trigger plasma injectors and the energy supplied to the trigger discharges, as well as adjusting the voltages applied to the main electrodes of the source. The proposed technical solution simplifies significantly the design of ion-plasma deposition systems intended for hybrid (combined) coating technologies. Experimental evaluation of the dual-mode pulsed plasma source in a hybrid coating-deposition process, in which the vacuum-arc mode is employed during the initial ion-cleaning stage and the magnetron mode during the subsequent coating-deposition stage, demonstrates that the deposited coatings exhibit high adhesion to the substrate and are free of cathode-material microdroplets, indicating the high quality of the deposited coatings.

Key words: vacuum-arc discharge, magnetron sputtering system, magnetic-field configuration, trigger injector, hybrid coating-deposition technologies.

У даній статті описано конструкцію та принцип дії розробленого дворежимного імпульсного плазмового джерела, здатного працювати як імпульсне вакуумно-дугове джерело плазми, так і як імпульсна магнетронна

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розпорошувальна система. Перехід між режимами роботи забезпечується зміною конфігурації магнетного поля у робочому об'ємі плазмового джерела, зміною послідовності спрацьовування пускових плазмових інжекторів та енергії, що вкладається в пускові розряди, а також зміною напруг живлення, які подаються на основні електроди джерела. Запропоноване технічне рішення значною мірою спрощує конструкцію йонно-плазмових установок, призначених для реалізації гібридних (комбінованих) технологій нанесення покриттів різного призначення. Практичні випробування дворежимного імпульсного плазмового джерела в гібридній технології нанесення покриттів, за якою на першому етапі (йонне очищення) використовувався вакуумно-дуговий режим роботи, а на другому етапі (безпосереднє нанесення покриття) — магнетронний режим, показали, що сформовані покриття характеризуються високою адгезією до основи та не містять мікрочастинок матеріалу катоди, що свідчить про їхню високу якість.

Ключові слова: вакуумно-дуговий розряд, магнетрона розпорошувальна система, конфігурація магнетного поля, пусковий інжектор, гібридні технології одержання покриттів.

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1. INTRODUCTION

Among the most widely used PVD methods for producing coatings of various purposes are the vacuum-arc method (arc-PVD) [1, 2] and the method employing magnetron sputtering systems (mss-PVD) [3, 4]. Both methods belong to ion-plasma technologies, and each of them possesses specific advantages and disadvantages. The principal devices used for coating deposition by ion-plasma methods are technological vacuum-arc plasma sources (arc evaporators) in vacuum-arc systems and magnetron sputtering systems (magnetrons) in magnetron-based technologies.

In recent years, so-called hybrid (combined) methods [5–8] have increasingly been employed in ion-plasma systems to obtain coatings of the highest quality. Such methods involve the application of several different surface treatment techniques within a single technological process, utilizing the most advantageous features of each method.

The main advantages of the vacuum-arc coating-deposition method are the high adhesion of the deposited surface layer to the substrate and the high processing productivity. Its principal disadvantage is the presence of microparticles of cathode material within the deposited coatings, typically in the form of microdroplets with sizes $\geq 2 \mu\text{m}$, which is inherent to the physical nature of vacuum-arc discharges [9–11]. The use of plasma filters [12] makes it possible to reduce the number of microparticles reaching the treated surface; however, this approach does not eliminate completely the problem.

Coatings deposited by the magnetron method do not contain cathode-material microparticles that ensures their structural uniformity. However, their adhesion to the substrate and the productivity of the process are lower than those in the vacuum-arc method. This is due to the lower degree of ionization of atoms sputtered from the cathode target and the lower main discharge currents compared with the vacuum-arc method.

At present, the implementation of hybrid coating-deposition methods combining vacuum-arc and magnetron techniques within a single technological process requires ion-plasma systems equipped with at least one technological vacuum-arc plasma source and one magnetron sputtering system. Such an expansion of functional capabilities can be realized, for example, in 'Bulat' systems by installing a magnetron on the vacuum chamber. The development of systems for hybrid PVD processes based on the 'domino' principle is described in [13].

Improvement in coating quality achieved by the hybrid method combining vacuum-arc and magnetron technologies is realized as follows. During the first stage (ion cleaning), a vacuum-arc plasma source is employed simultaneously with the application of a high negative potential to the products. This ensures high coating adhesion to the substrate and heats the products to the required temperature, thereby improving the conditions for coating formation. After completion of ion cleaning, the second stage begins, during which the voltage applied to the substrate holder is reduced, the magnetron sputtering system is activated, and the coating is deposited by a flux of sputtered particles free from cathode material microparticles.

A significant disadvantage of such a combined method is the increased complexity of the equipment required for its implementation, since the coating-deposition system must incorporate two different types of particle sources responsible for coating formation.

The aim of this work is to develop the design of a pulsed plasma source capable of operating, depending on the selected mode, either as a pulsed vacuum-arc plasma source or as a magnetron sputtering system.

2. DESIGN OF THE DUAL-MODE PULSED PLASMA SOURCE

2.1 Basic Requirements for the Design of the Dual-Mode Pulsed Plasma Source

During the development of the dual-mode pulsed plasma source design, it was necessary to satisfy a number of requirements that would enable the plasma source to generate a plasma flux, while operating in two modes: either vacuum-arc discharge mode or magnetron discharge mode.

The principal requirements for vacuum-arc evaporators operating in a steady-state mode are presented in Refs. [1, 2]. When a vacuum-arc source operates in a pulsed mode, an additional requirement arises, namely, ensuring uniform cathode wearing.

As regards pulsed magnetron sputtering systems [3, 4], the operating requirements largely coincide with those for vacuum-arc plasma sources. The major difference between these types of plasma sources lies in the different magnetic field configurations required for their operation, as well as in the voltages that must be applied to the main electrodes of the devices and the operating modes of the trigger plasma injectors.

Thus, by creating conditions under which both vacuum-arc and magnetron discharges can be sustained sequentially within a single device through variation of the magnetic field configuration and other parameters, the implementation of the hybrid method can be significantly simplified.

2.2 Design of the Pulsed Plasma Source

The design of the dual-mode pulsed plasma source, which satisfies the requirements for operation in the mode of a pulsed vacuum-arc plasma source and, upon modification of the magnetic-field configuration and the operating mode of the trigger plasma injectors, provides transition to the mode of a pulsed magnetron sputtering system, is shown in Fig. 1.

The pulsed plasma source consists of an anode 1, at one end of which a consumable disc cathode 2 with an electromagnet 3 is coaxially mounted, while at the opposite end a substrate holder 4 with the treated products 5 is installed. By means of flange 6 and insulating gasket 7, the cathode is vacuum-tightly connected to the anode. The anode is surrounded by electromagnet 8 (the power supplies of electromagnets 3 and 8 are not shown in Fig. 1). The trigger plasma injectors TI_1-TI_{12} are installed within the anode body near cathode 2.

Each trigger plasma injector consists of an igniting electrode 9 (*IE*) and a cathode electrode 10 (*CE*), both made in the form of rectangular cross-section rods and placed inside a ceramic housing 11. The housing of each trigger plasma injector is vacuum-tightly integrated into the anode. The pulsed power supply unit PPS_0 of the main discharge between the anode and cathode includes a storage capacitor C_0 connected to the main power supply MPS_0 , and a switching element S_0 , the control terminal of which is connected to the control unit *CU*. The trigger plasma injectors TI_1-TI_{12} are powered by pulsed power supply units PPS_1-PPS_{12} (the units PPS_1-PPS_{12} and their connections to the arc power supply *APS* and the magnetron power supply *MPS* are shown schematically in Fig. 1).

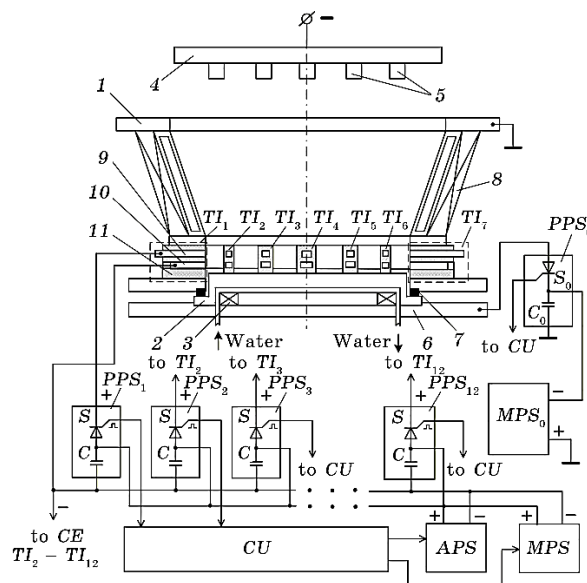


Fig. 1. Schematic diagram of the dual-mode pulsed plasma source and its power supply system: 1 is anode, 2 is cathode, 3 is solenoid, 4 is substrate holder, 5 are products, 6 is flange, 7 is insulator, 8 is solenoid, 9, 10 are electrodes of the trigger plasma injector, 11 is ceramic housing of the injector, TI_1 – TI_{12} are trigger plasma injectors, PPS_0 is pulsed power unit for the main discharge between the anode and cathode, PPS_1 – PPS_{12} are pulsed power units for the trigger plasma injectors (shown schematically), MPS_0 , APS, and MPS are power supplies, CU is control unit, CE is cathode electrode of the trigger plasma injector.

2.3 Features of the Components and Units of the Dual-Mode Pulsed Plasma Source

Unlike the plasma injectors used in vacuum-arc plasma sources for arc excitation, which typically have a cylindrical shape [13], the developed dual-mode pulsed plasma source employs trigger injectors of rectangular shape, as shown in Fig. 2.

In this case, the electrodes of the trigger injector have a rod-shaped configuration and are fabricated from the same material as the cathode. The increased cross-sectional area of the cathode electrode of the injector, compared with that of the igniting electrode, is explained by the formation of a cathode spot of the trigger discharge on its surface [14], which results in more intensive wearing compared with the igniting electrode. Such design solutions ensure the absence of impurities in the plasma generated by the dual-mode pulsed plasma source and provide a long service life of the main discharge ignition system.

During the fabrication of the trigger injector, electrodes were vac-

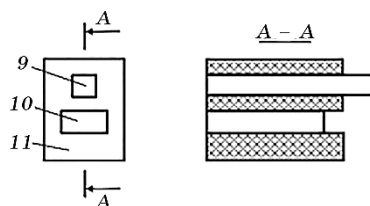


Fig. 2. Design of the trigger plasma injector: 9 is igniting electrode (IE), 10 is cathode electrode (CE), 11 is ceramic housing.

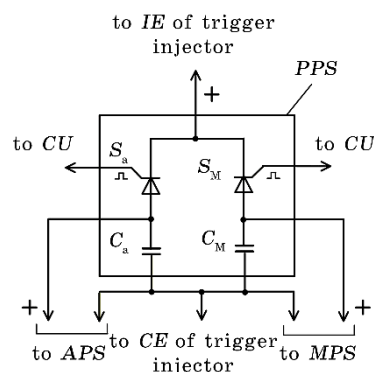


Fig. 3. Electrical circuit diagram of the trigger plasma-injector power supply unit.

uum-tight mounted into a housing made of 22KhS ceramic using sodium silicate ($\text{Na}_2\text{SiO}_3 \cdot 9\text{H}_2\text{O}$), following the procedure described in [15]. The trigger injectors were likewise vacuum-tight mounted into the anode, using the same technological procedure.

Each operating mode of the pulsed plasma source requires the corresponding operation of the trigger injectors, which ensure reliable excitation of either the vacuum-arc discharge or the magnetron discharge between the anode and cathode of the device. The operating mode of the trigger injectors is determined by the control unit *CU*, which regulates the operation of the plasma injector power supply units PPS_1 – PPS_{12} . The electrical circuit employed in the design of the trigger plasma injector power supply units is shown in Fig. 3.

3. OPERATING PRINCIPLES OF THE DUAL-MODE PULSED PLASMA SOURCE

After the preliminary surface preparation, the products 5 are mounted on the substrate holder 4. The vacuum chamber (not shown in Fig. 1) is then sealed and evacuated to a pressure of approximately 10^{-3} Pa. Sub-

sequently, the pulsed plasma source power supply system is activated. This includes the power supplies MPS_0 , APS , and MPS , which charge the capacitors C_0 , C_a , and C_m located in the pulsed units PPS_0 and PPS_1 – PPS_{12} , respectively. In the present study, the capacitances of C_0 , C_a , and C_m were of 100.0 μF , 40.0 μF , and 2.0 μF , respectively. These capacitors were charged to the following voltages: 800 V for C_0 , 500 V for C_a , and 700 V for C_m .

The coating-deposition process subsequently begins with the ion-cleaning stage, during which the pulsed plasma source operates in the vacuum-arc mode. Upon receiving a command from the control unit CU, the power supplies of electromagnets 3 and 8 are energized, thereby, generating a combined and co-ordinated magnetic field.

The pulsed vacuum arc is ignited by means of trigger plasma injectors TI_1 – TI_{12} . A triggering voltage is applied to the igniting electrode 9 (IE) of each injector from the pulsed units PPS_1 – PPS_{12} (supplied by capacitors C_a ; Fig. 3) through the switching elements S_a (TB161-80-12 thyristors), which are controlled by the CU (Fig. 1).

The cathode electrodes 10 (CE) of the trigger plasma injectors TI_1 – TI_{12} are permanently connected to the second terminals of capacitors C_a and C_m . Application of the triggering voltage to a plasma injector initiates a surface discharge along the dielectric separating its electrodes. As a result, a cathode spot is formed on the cathode electrode of the injector, generating a plasma plume in the vicinity of the working surface of cathode 2. Simultaneously, upon activation of the switching elements S_a , the control unit also switches on the main switching element S_0 (TB2-160-10 thyristor). Consequently, a voltage is established between anode 1 and cathode 2. In the presence of the plasma plume near the cathode surface, this voltage initiates a pulsed vacuum-arc discharge between the anode 1 and cathode 2 of the device.

The pulse repetition frequency of the vacuum-arc discharge was of 800 Hz, while the peak arc current reached 450 A. To increase the service life of the arc ignition system and to ensure uniform wearing of the cathode 2, the trigger plasma injectors were activated sequentially in a cyclic manner according to the algorithm implemented in the control unit. The energy supplied to each trigger discharge was of 5 J.

The cathode spots generated by the pulsed arc discharge transform the cathode material into a plasma state. The resulting cathode-material ions are accelerated by the bias voltage applied to the substrate holder 4 and the products 5 during this stage (the bias voltage was of 1000 V) and bombard the product surfaces, thereby providing simultaneous surface cleaning and heating. This process continues until the products 5 are heated to the required temperature (of approximately 500°C for P6M5 high-speed steel) and their surfaces become sufficiently cleaned and activated for the deposition of high-quality coatings. Once these conditions are achieved, the ion-cleaning stage is ter-

minated, and the process proceeds to the coating-deposition stage.

The coating-deposition process was carried out with the pulsed plasma source operating in the magnetron discharge mode. To switch to this operating mode, the power supplies of electromagnets 3 and 8 were reconfigured by the control unit *CU* to generate an opposing magnetic field. Simultaneously, the bias voltage applied to the substrate holder was reduced to 150 V, while the pressure in the vacuum chamber was increased to $2 \cdot 10^{-1}$ Pa by introducing the reactive gas (nitrogen).

The magnetron discharge between anode 1 and cathode 2 was initiated, using trigger plasma injectors TI_1 – TI_{12} . A triggering voltage from pulsed units PPS_1 – PPS_{12} was applied to the injector electrodes through the switching elements S_m (TCh-50-9 thyristors), which were controlled by the *CU*. This resulted in the simultaneous activation of all plasma injectors and the discharge of the energy stored in capacitors C_m into the trigger discharge. Under these operating conditions, the energy delivered to the trigger discharge of each injector was of 0.49 J.

Unlike the ion-cleaning mode, all trigger plasma injectors were activated simultaneously, producing a plasma cloud uniformly distributed over the working surface of the cathode 2. At the same time, similarly to the ion-cleaning stage, a voltage from the pulsed power unit PPS_0 was applied between anode 1 and cathode 2 by switching on the element S_0 in response to a command from the control unit. In the presence of the plasma cloud near the cathode surface and the magnetic field of the required configuration, these conditions resulted in the ignition of a pulsed magnetron discharge between anode 1 and cathode 2 of the plasma source.

The pulse repetition frequency of the magnetron discharge was 1000 Hz, while the peak discharge current reached 25 A. The atoms and ions sputtered from cathode 2 in the magnetron discharge were transported toward the substrate holder and deposited onto the surfaces of the products 5, thereby, forming the coating. The deposition process continued until a coating thickness of 2 μ m was achieved.

4. RESULTS AND DISCUSSION

Characterization of the coatings deposited using the proposed pulsed plasma source demonstrated that their adhesion to the substrate was comparable to that of conventional vacuum-arc coatings. At the same time, the deposited coatings were free of cathode material microdroplets, which are typically observed in vacuum-arc deposition processes. Furthermore, the coatings consisted exclusively of the cathode material without detectable impurities. These results indicate the high quality of the deposited coatings.

The proposed pulsed plasma source was used to deposit coatings on 15 batches of products under the operating conditions described above.

Throughout the experimental campaign, no failures were observed in the ignition of either the pulsed vacuum-arc discharge or the pulsed magnetron discharge, demonstrating the high reliability of the discharge ignition system.

Thus, the proposed design successfully achieves the intended technical objectives. Specifically, it extends the functional capabilities of the pulsed plasma source by enabling stable operation in both the magnetron discharge mode and the vacuum-arc discharge mode. In addition, the proposed ignition system provides enhanced reliability of the main discharge initiation in both operating modes and contributes to the deposition of high-quality coatings.

5. CONCLUSIONS

A pulsed plasma source capable of operating in both the pulsed vacuum-arc mode and the pulsed magnetron sputtering mode has been developed. Transition between the two operating modes is achieved by modifying the magnetic-field configuration within the plasma source, changing the activation sequence of the trigger plasma injectors and the energy supplied to the trigger discharges, as well as adjusting the voltages applied to the main electrodes. These operating conditions are implemented by the power supply circuit of the plasma source.

The design features of the dual-mode pulsed plasma source are presented, with particular emphasis on the trigger plasma injectors and their operating principles in each discharge mode.

Experimental evaluation of the dual-mode pulsed plasma source in a hybrid coating-deposition process, in which the plasma source operated in the vacuum-arc mode during the initial ion-cleaning stage and in the magnetron mode during the subsequent coating-deposition stage, demonstrated that the deposited coatings exhibited high adhesion to the substrate and were free of cathode material microdroplets. These results confirm the high quality of the deposited coatings.

The proposed plasma source significantly simplifies the design of ion-plasma coating systems intended for hybrid (combined) coating technologies by enabling both ion cleaning and coating deposition to be performed using a single plasma source operating in two different discharge modes.

AUTHORS' CONTRIBUTIONS

S. Iu. O. proposed and developed the operating principle of a plasma source capable of operating in two modes: as a vacuum-arc plasma source and, by changing the magnetic-field configuration, as a magnetron sputtering system. Sh. Yu. V. developed the design of the plasma

source, prepared the technical drawings, and provided further details of the operating principle of the developed plasma source. F. K. V. investigated the characteristics of the developed plasma source. All authors approved the final version of the manuscript.

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