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Pulsed Vacuum-Arc Plasma Source for Multicomponent Coatings

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The design and operating principle of a pulsed vacuum-arc plasma source for obtaining multicomponent coatings are presented. The proposed composite cathode assembly of this plasma source has a base made of a metal with high thermal conductivity, shaped like a cylinder with end surfaces, one of which is cooled. The cathode base has through holes arranged uniformly concentrically around the axis of the base, into which cylindrical inserts made of metals included in the coating composition are vacuum-sealed. The inserts are made in the form of sleeves with an insulator containing an igniting electrode tightly fitted inside each insert. In the case when the base material is part of the coating composition, instead of at least one hole for the insert, the cylindrical base has holes, into which insulators with igniting electrodes are vacuum-sealed. The principles of operation of the pulsed plasma source with the proposed composite cathode assembly for producing multicomponent coatings of a specified composition are described. Practical tests of the developed plasma source in the 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 aluminium) at varying pulse frequencies demonstrated that the obtained multicomponent coatings closely match the specified composition, and the pulsed plasma source is characterized by reliable performance.

Key words: vacuum-arc coatings, multicomponent coatings, vacuum-arc discharge, pulsed plasma source, composite cathode assembly.

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Наведено конструкцію й описано принцип дії імпульсного вакуумно-дугового джерела плазми для одержання багатокомпонентних покриттів. Запропонований складовий катодний вузол такого джерела плазми має основу, виконану з металу, що має високу теплопровідність, у вигляді циліндра з торцями, один з яких охолоджується. В основі катоди виконано наскрізні отвори, які розташовані рівномірно по концентричних колах відносно осі основи і в які вакуумно-щільно вмонтовано циліндричні вставки з металів, що входять до складу покриття. Вставки виконано у формі втулок; всередину кожної втулки щільно вмонтовано ізолятор з підпалювальною електродою. У випадку, коли матеріял основи входить до складу покриття, замість, як мінімум, одного отвору для втулки у циліндричній основі виконано отвори, в якій вакуумно-щільно вмонтовано ізолятори з підпалювальною електродою. Описано принципи дії імпульсного джерела плазми із запропонованим складовим катодним вузлом для одержання багатокомпонентних покриттів заданого складу. Практичні випробування розробленого джерела плазми у режимі нанесення покриттів (амплітудне значення струму дуги — 420 А, тривалість імпульсів дуги на титані — 50 мкс, на молібдені — 45 мкс, на алюмінії — 665 мкс) за різних частот проходження імпульсів показали, що одержані багатокомпонентні покриття мають склад, близький до заданого, а само імпульсне джерело плазми характеризується надійною роботою.

Ключові слова: вакуумно-дугові покриття, багатокомпонентні покриття, вакуумно-дуговий розряд, імпульсне джерело плазми, складовий катодний вузол.

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1. INTRODUCTION

The requirements for extending the service life of machine parts and cutting tools in various industries impose special conditions on the formation of their surface layers. One of the leading methods of obtaining coatings with high functional characteristics is vacuum-arc technologies [1–3].

Recently, multicomponent coatings are increasingly used, when creating of coatings with enhanced functional characteristics. Composite cathodes (various systems of Ti–Si [4], Ti–V–Zr–Nb–Hf [5], *etc.*) and gas mixtures (reactive in various combinations with the addition of inert gases [6, 7]) are used for this purpose. The number of types of multicomponent coatings, including multilayer, gradient, nanostructured ones, available on the tool-making market, currently exceeds a hundred [8, 9].

To form multielement vacuum-arc coatings, it is necessary to create multicomponent plasma, from which their condensation occurs. There are two main methods for generating such plasma: creating multiple streams of metal plasma directed into the condensation zone with

evaporating two or more monoelement cathodes, and generating multielement plasma by evaporating composite cathodes containing several elements. The first method requires the use of multiple plasma sources with monoelement cathodes, which leads to a significant increase in the equipment costs for its implementation. Therefore, in practice, the second method of creating multielement plasma is typically used—with composite cathodes.

Materials for composite cathodes can be produced using methods of vacuum remelting [10, 11], powder technologies [12], self-propagating high-temperature synthesis (SHS) [13], *etc*. The use of cathodes made of such materials allows for obtaining multielement coatings, but their production is characterized by time-consuming and technologically complex tasks, as well as high equipment costs for their implementation.

Composite (mosaic) cathodes are much simpler to manufacture. They have a design when the base of the cathode made of one metal includes inserts made of other elements (metals). The design of one of the first such cathodes is described in [14]. Subsequently, composite cathodes with a number of inserts reaching several dozen were developed [15, 16].

Vacuum-arc plasma sources with composite cathodes allow for obtaining multicomponent coatings of the required composition. However, they have two significant drawbacks. Firstly, in composite cathodes, uneven wear of the cathode working surface occurs due to differences in the electron transport coefficients for different metals. For example, inserts made of aluminium or copper (which have a similar electron transport coefficient, around 120 μg/K [17]) will wear out almost four times faster than inserts made of titanium or chromium (with an electron transport coefficient of around 40 μg/K [17]) under the same conditions.

Secondly, the design of the known composite cathode assemblies is intended for their use in vacuum-arc plasma sources operating in stationary vacuum arc mode. Such a discharge is characterized by a significant number of macroparticles (droplets) of cathode material in the plasma flow, which enter the coating, reducing its quality (in the ion cleaning mode, there are about 30% cathode material droplets in the condensate, and in the deposition mode 20% [18]).

There are much fewer macroparticles (droplets) of cathode material in the plasma flow generated in the pulsed mode of a vacuum arc lifetime [19], which allows for obtaining higher-quality coatings. However, composite cathodes in their current form, as used in stationary vacuum-arc plasma sources, cannot be used in pulsed plasma sources. Therefore, the development of a pulsed vacuum-arc plasma source with the composite cathode assembly to obtain high-quality multicomponent coatings is a relevant task.

2. DESIGN OF A PULSED VACUUM-ARC PLASMA SOURCE

2.1. Design Features of the Pulsed Vacuum-Arc Plasma Source

The schematic design of the developed pulsed vacuum-arc plasma source is shown in Fig. 1. It consists of the pulsed vacuum-arc plasma source itself *1* and its power supply circuit *2*.

The pulsed vacuum-arc plasma source *1* comprises an anode *3* and a cathode assembly *4*. The anode and cathode assembly are enclosed by a solenoid (not shown in Fig. 1), which generates an axisymmetric uniform magnetic field within the plasma source.

The cathode assembly contains a base *5* made of a highly thermally conductive metal (aluminium was used) in the form of a cylinder (60 mm in diameter) with end surfaces, one of which is cooled (marked as *6* in Fig. 1). Cylindrical inserts *7*, shaped like sleeves and made of metals used in the coating composition, are vacuum-sealed into through holes in the base *5*.

The inserts *7* are of uniform size (outer diameter of 11 mm, inner

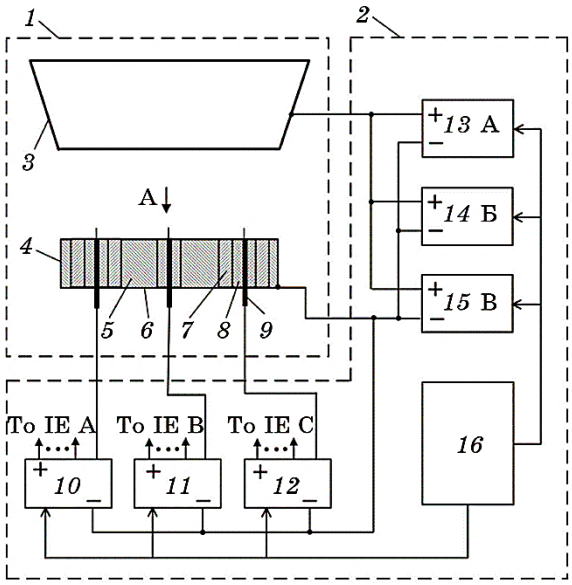

Fig. 1. Pulsed vacuum-arc plasma source with the composite cathode assembly: *1* is vacuum-arc plasma source schematic, *2* is power supply circuit, *3* is anode, *4* is cathode assembly, *5* is base of the cathode assembly, *6* is cooled end surface of the composite cathode, *7* is cylindrical inserts made of metals used in the coating composition, *8* is insulator, *9* is igniting electrode, *10*, *11*, *12* are igniting blocks, *13*, *14*, *15* are vacuum arc power supply blocks, *16* is control unit.

diameter of 5 mm) and have a length equal to the thickness of the base (10 mm). Inside each insert, an insulator *8* (diameter of 5 mm) with an igniting electrode *9* (diameter of 2 mm) is tightly fitted. The working surfaces of the inserts, insulator, and igniting electrode are flush with the working end surface of the base, opposite to the end surface *3*, which improves the manufacturing conditions of the cathode assembly and enhances the reliability of vacuum-arc ignition.

The operation of the pulsed vacuum-arc plasma source *1* is supported by the power supply circuit *2*. This circuit consists of igniting blocks *10*, *11*, *12* and pulsed vacuum arc power supply blocks *13*, *14*, *15*, which are connected to the control unit *16* at the control input. The outputs of igniting block *10* are connected to the igniting electrodes *9* of the inserts made of the first metal (group of inserts A, made of titanium). The outputs of igniting block *11* are connected to the igniting electrodes *9* of the inserts made of the second metal (group of inserts B, made of molybdenum), and the outputs of ignition block *12* are connected to the igniting electrodes *9* of the inserts made of the third metal (group of inserts C, made of aluminium). In Figure 1, these are labelled 'To IE A', 'To IE B', and 'To IE C'. The outputs of the pulsed vacuum arc power supply blocks *13*, *14*, and *15* are connected to the anode and cathode of the pulsed vacuum-arc plasma source *1*, where power supply block *13* supplies the arc on the group of inserts A, block *14* supplies the arc on the group of inserts B, and block *15* supplies the arc on the group of inserts C, ensuring the necessary arc pulse durations for each material. This circuit design provides the required frequency, duration, and sequence of pulsed arc discharges on each group of inserts to produce multicomponent coatings of the specified composition with an even distribution of components.

The cathode assembly *4* shown in Fig. 2 (view A from the anode *3* in Fig. 1) illustrates the case when the base material of the cathode *5* is part of the coating composition. It includes six inserts made of titanium (denoted by Ti, material of group A), with insulators *8* and igniting electrodes *9* embedded in them, uniformly arranged along the concentric circle *17* relative to the axis of the cathode base. Five inserts made of molybdenum (denoted by Mo, material of group B), with embedded insulators *8* and igniting electrodes *9*, are evenly positioned along the concentric circles *17* and *18* around the cathode base axis. Two 'inserts' made of the base material (aluminium, denoted by Al, material of group C), with embedded insulators *8* and igniting electrodes *9*, are positioned as follows: one in the centre of the cathode base and the other along the concentric circle *17* (a design where igniting units are embedded in the cathode base can be conditionally regarded as the putting of two aluminium 'inserts' in the base). The cathode base wearing zone is marked by a dashed circle *19* in Fig. 2, indicating the area where the aluminium 'inserts' wear down.

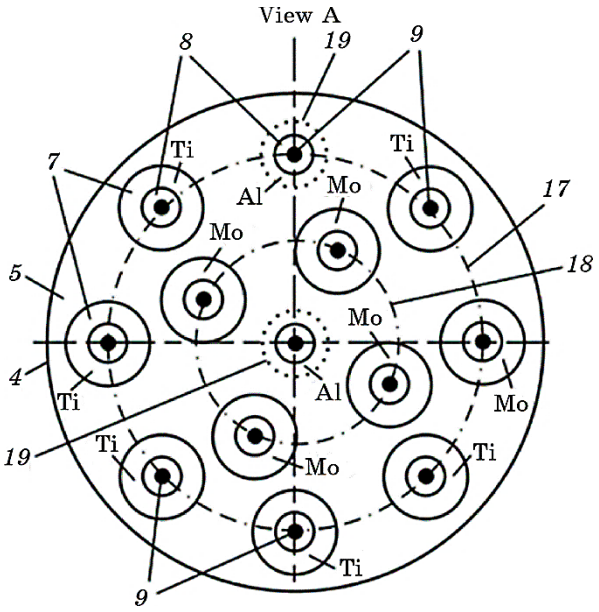

Fig. 2. Cathode assembly of the pulsed vacuum-arc plasma source: *17*, *18* are circles concentric to the axis of the cathode base, *19* is wearing zone of the cathode base material, other positions as in Fig. 1.

The selection of the insert dimensions was made based on the following considerations. The length of the inserts was chosen to simplify the manufacturing technology of the composite cathode and to improve the cooling conditions of the inserts. The issue of optimal balance between the reserve of plasma-forming material in the insert and the stability of arc excitation and burning on its working surface was also taken into account. The outer and inner diameters of the inserts were determined as follows: the outer diameter was chosen based on the duration of the arc pulses and the uniform arrangement of inserts in the cathode base with a diameter of 60 mm, which was dictated by the design of the plasma source based on the standard plasma source of the 'Булат-6' installation; the inner diameter was determined by the minimum possible diameter of the insulator in the arc excitation system that ensures its reliable operation.

2.2. Ensuring the Airtightness of the Cathode Assembly

To ensure the airtightness between the working end and the cooled end surfaces of the cathode assembly, the assembly was manufactured as follows. First, a layer of bonding material was applied in the connection area on the metal inserts *7*, insulators *8* (ceramic tubes of 22XC

material), and igniting electrodes *9*. Sodium silicate $Na_2SiO_3 \cdot 9H_2$ was used as the bonding material. After holding these components at room temperature for an hour, they were assembled and then placed in a shaft-type muffle furnace, where the temperature was gradually increased to 1200°C. After holding at this temperature for 30 minutes and then allowing the components to cool, the assemblies made up of elements *7*, *8*, and *9* were complete. In the next stage, the assembled units were press-fitted into the holes of the cathode base *5*, ensuring airtightness [24]. This completed the manufacturing process of the composite cathode assembly.

3. PRINCIPLES OF OPERATION OF THE PULSED PLASMA SOURCE WITH THE COMPOSITE CATHODE

3.1. Ensuring Effective Cooling of the Cathode Assembly

In the proposed cathode assembly, one of the primary functional purposes of the cathode base is to cool the inserts, which is best achieved by using a metal with high thermal conductivity. For example, the thermal conductivity of aluminium is more than an order of magnitude higher than that of one of the most common cathode materials, titanium [20]. Thus, the proposed cathode assembly offers cooling conditions that are over an order of magnitude better. Furthermore, cooling the inserts in the proposed manner (not only from the cooled end surface but also along the lateral surface) is the most effective way to maintain the inserts temperature during operation at a low level, close to the temperature of the coolant. Additionally, the uniform arrangement of the inserts (equidistant from each other) in concentric circles relative to the base axis further contributes to their effective cooling. This cooling regime for the inserts during the cathode assembly operation ensures its low temperature, which in turn reduces the number of droplets in the plasma flow of the source [19, 21], leading to the production of high-quality coatings.

3.2. Ensuring Reliable Excitation of the Pulsed Vacuum Arc

To ensure the excitation of the vacuum arc, the inserts are designed as sleeves, inside which insulators with igniting electrodes are tightly fitted. When a start pulse is applied to the igniting electrode, initial plasma is generated, which leads to the formation of a cathode spot of the pulsed arc. This solution allows sequential ignition of the vacuum arc on each insert according to the timing algorithm needed to produce coatings of the desired composition. This approach increases the service life of the vacuum arc excitation system on the plasma source

cathode assembly by a factor of N, where N is the number of ignition units used, thereby enhancing the reliability of the plasma source with the proposed cathode assembly by the same factor. Moreover, this technical solution enables the plasma source to operate in the pulsed mode with pulse durations in the microsecond range. This reduces the number of macrodroplets in the plasma flow [19] compared to a stationary arc, thus, improving the quality of coatings applied to the substrate.

In our conditions, with the presence of the axisymmetric uniform magnetic field, there was no 'attachment' effect of the cathode spot to the metal–dielectric boundary during its excitation, similar to findings in Ref. [22]. This may also be attributed to the fact that current was supplied to the inserts through the aluminium cathode base.

3.3. Determining the Duration of Arc Pulses on Inserts Made of Different Metals

Excitation of the vacuum arc using the insulator with the ignition electrode on the working end surface of the insert leads to the evaporation of the insert metal and its penetration into the coating. Achieving conditions when the cathode spot of the arc remains only on the working end surface of the insert (thereby, preventing any unintended contribution of the composite cathode base material into the coating) is possible exclusively in the pulsed mode of the vacuum arc with pulse durations limited to the time required for the cathode spot to move from its ignition point (the boundary on the working surface of the insert between its inner surface and the insulator) to the boundary between its outer surface and the surface of the base. Since this distance is small (a few millimetres) and the cathode spot movement speed can reach several tens of meters per second or more, the vacuum arc pulse duration cannot exceed several tens of microseconds. It is also necessary to consider that the speed of the cathode spot movement depends on the material it exists on and the strength of the magnetic field, which is typically present in plasma sources to focus the plasma flow onto the substrate holder. Therefore, the arc-discharge duration on inserts made of different metals will vary to meet the condition of confinement only on the inserts working surface.

To determine the arc-pulse duration when the cathode spot remains confined to the insert working surface, studies were conducted for different insert materials using the setup shown in Fig. 3. Cathodes were fabricated with inserts (13 in total) made of only one of the composite cathode materials (in this case, titanium or molybdenum) that contributed to the coating composition. After installing this cathode in the pulsed plasma source and placing a sample on the substrate holder, the source operated for 15 minutes in a mode when the pulsed arc was ex-

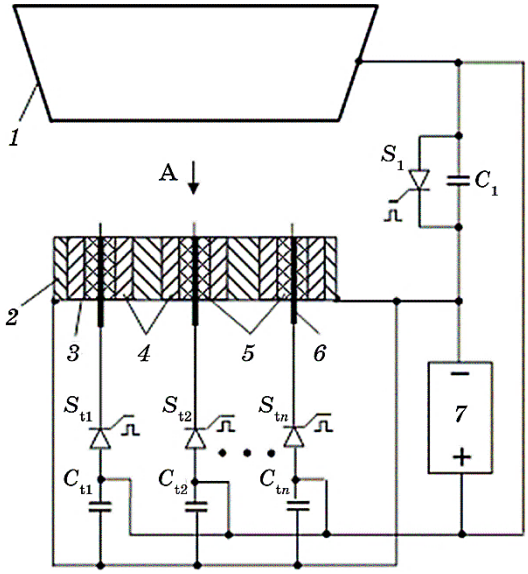

Fig. 3. Pulsed vacuum-arc plasma source for determining arc pulse duration: *1* is anode, *2–6* are components of the composite cathode assembly, *7* is power supply unit, C_1 is arc power capacitor, C_{t1}–C_{tn} are igniting capacitors, S_1, S_{t1}–S_{tn} are switching elements.

cited only on one insert with arc-pulse duration of 30 μs (the arc-pulse duration was controlled by the switching element S_1, which activation interrupted the arc discharge). The initial arc pulse duration was selected to ensure that the arc cathode spot remained on the working surface of the insert of this material.

Next, the coating composition on the obtained sample was analysed using the energy-dispersive microanalysis system of the PEM-106 scanning electron microscope. If no base material (aluminium) was detected in the coating, the process was repeated—another sample was loaded into the vacuum chamber, and the coating was applied by the cathode assembly operating on the next insert with an increased pulsed arc discharge duration by 5 μs (adjustments to the thyristor S_1 activation time were provided by its control system, not shown in Fig. 3.

This process continued until aluminium appeared in the coating on the sample. Then, the maximum arc pulse duration for the given insert material, when the cathode spot of the pulsed arc remained only on the working surface of the insert, was determined as the last pulse duration when aluminium was absent in the sample coating. The conducted studies showed that the base material did not appear in the coatings on the samples at maximum arc pulse durations of 50 μs for titanium inserts and 45 μs for molybdenum inserts.

In cases when the base material (aluminium) was included in the coating composition, certain factors should be considered. The speed of the cathode spot movement on aluminium is nearly an order of magnitude lower than on titanium and molybdenum [1], and the electron-transport coefficient is three times higher than that of these metals [17]. Thus, achieving an equal amount of material contribution to the coating over a given deposition time from both aluminium 'inserts' and inserts made of other metals can be managed by adjusting either the arc pulse duration or arc pulse frequency on these inserts, or by simultaneously regulating both parameters. It is essential to ensure that the base material wear occurs within zone *19* (Fig. 2), which reliably prevents the cathode spot from reaching the inserts made of other metals when the cathode assembly design in Fig. 2 is used.

The significant difference in the movement speed of the cathode spot on aluminium compared to other insert materials at equal vacuum arc pulse durations will result in substantial variation in the wearing (evaporation) zones on inserts made of these metals. For instance, with vacuum-arc pulse duration of 50 μs, the width of the wearing zone on the titanium insert will be about 2.5 mm, whereas on the aluminium 'insert', this zone width will not exceed 0.15 mm. Such a small erosion zone on the aluminium 'insert' will lead to its rapid wear and to the cathode spot sinking deeper into the 'insert'. This, in turn, will reduce the reliability of arc excitation on it and cause arc-pulse failures on the 'insert'. Such a process is undesirable, as it will uncontrollably decrease the aluminium content in the coating.

To prevent this phenomenon, it is necessary to increase the wearing zone on materials with a low cathode spot movement speed. This can be achieved by extending the duration of vacuum arc pulses on such materials. For example, by increasing the arc pulse duration on the aluminium 'insert' to 665 μs, the wearing zone close to 2 mm can be obtained, which is already acceptable.

The pulsed operation mode of the plasma source with arc-pulse durations in the tens of microseconds ensures the wear only the inserts materials with a minimal number of droplets entering the coating [19, 23]. Moreover, walls formed during insert wear act as barriers that prevent droplets from entering the generated plasma flow [15], thus, improving the coating quality.

3.4. Correlation between Insert Material Content in the Coating and Other Parameters

The quantity of material m_{ki} of inserts made of the same metal that enters the coating can generally be determined as follows:

$$m_{ki} = \mu k N_1 N_2 I_d t, \tag{1}$$

where μ is the electron-transport coefficient of the insert metal, k is the coefficient accounting for the fraction of evaporated metal that enters the coating (dependent on the design of the plasma source), N_1 is the number of inserts made of the same material, N_2 is the number of vacuum-arc discharges occurring on an insert, I_d is the average current of the vacuum-arc discharge during a pulse, and t is the duration of the vacuum arc pulse.

The area of the inserts S_{ki}, of which one type of metal evaporates, is determined as follows:

$$S_{ki} = 2\pi r_m h N_1, \tag{2}$$

where r_m is the average radius of the insert ring, h is the width of the ring of the insert working surface (the difference between the inner and outer radii).

After the cathode spot of the vacuum-arc discharge appears, it begins to move chaotically across the working surface of the insert. For a chaotic movement of the cathode spot, the maximum possible displacement x over a time interval t can be defined as follows [24]:

$$x^2 = 0.5\pi \frac{r_0^2}{\tau} t\,, \tag{3}$$

where r_0 is the size of the cathode spot cell, τ is the lifespan of an individual cathode spot cell.

Since the displacement x cannot exceed h, the following equation can be used to establish the relationship between the content of the insert material m_{ki} in the coating and other parameters of the composite cathode, as well as its operating mode:

$$m_{ki} = \frac{\mu k N_1 N_2 I_d \tau S_{ki}^2}{2\pi^3 r_m^2 r_0^2}\,. \tag{4}$$

The provided dependence (4) allows only for an approximate assessment of the correlation between the total working surface area of inserts made of the same metal and the amount of that metal in the coating. This is due to several factors: the spontaneous behaviour of the vacuum arc cathode spot (for example, the relationship between r_0^2 and τ (r_0^2 / τ) given in Ref. [25] is estimated at around 10^{-3}–10^{-2}, indicating an error margin of at least an order of magnitude); the electron transport coefficients reported in the literature vary significantly; and the speed of the cathode spot movement is influenced by factors other than the cathode material, such as the presence and intensity of the magnetic field, the pressure and type of the gas in the plasma source volume, and other conditions.

It is also worth noting the following: to produce a titanium film with

a thickness of one micrometre under similar conditions, approximately $1.5 \cdot 10^5$ activations of the pulsed vacuum-arc plasma source are needed [26]. This indicates that, when operating in pulsed mode with pulse durations of several tens of microseconds, the existence of a vacuum arc on each material in the composite cathode enables the formation of multicomponent coatings with high precision in composition.

4. RESULTS AND DISCUSSION

The composite cathode was fabricated according to Fig. 2 for testing purposes. This composite cathode assembly was installed in a pulsed vacuum-arc plasma source, which was then set up in the vacuum chamber of the 'Булат-6' installation. To monitor the composition of the coating, three samples were placed in the vacuum chamber in each test series, onto which coatings were deposited.

The vacuum chamber was evacuated to the working pressure ($2 \cdot 10^{-3}$ Pa), and coatings of the specified composition were deposited onto the samples by sequentially initiating pulsed vacuum-arc discharges on the working surface of the inserts through electrical breakdown across the end surface of the insulator between the igniting electrode and the cathode.

These igniting discharges were initiated by applying voltage to the igniting electrodes from one of the igniting blocks (*10*, *11*, or *12*, Fig. 1), depending on which insert material (group A, B, or C) was to be deposited on the sample at a given moment of plasma source operation. The igniting blocks were managed by control unit *16*, Fig. 1, which simultaneously with the igniting blocks activation signal turned on the vacuum arc power supply blocks (*13*, *14*, or *15*, Fig. 1) to provide the required duration of vacuum arc pulses depending on the material group of the insert. The resulting cathode arc spot then began moving randomly across the working end surface of the insert, generating a plasma flow, from which the coating was deposited.

Three modes for depositing multicomponent coatings of specified compositions were implemented. In mode 1, the target coating composition was of 33.4% titanium, 33.3% molybdenum, and 33.3% aluminium. In mode 2, the coating composition was set to 72.7% titanium, 9.1% molybdenum, and 18.2% aluminium. In mode 3, the specified coating composition was of 12.5% titanium, 62.5% molybdenum, and 25.0% aluminium.

A specific algorithm programmed in control unit *16* managed the appropriate mode for depositing coatings. In all modes, control unit *16* provided control pulses to igniting blocks *10*, *11*, *12* and corresponding power supply blocks *13*, *14*, *15*, ensuring sequential activation of both groups of inserts and individual inserts within each material group. This approach facilitated an even distribution of materials in the coat-

ing composition.

The algorithm in control unit *16* provided the following timing parameters for each coating-depositing mode. Mode 1: on titanium inserts—arc-pulse frequency of 40 Hz with a duration of 50 μs, on molybdenum inserts—arc-pulse frequency of 40 Hz with a duration of 45 μs, on aluminium inserts—arc-pulse frequency of 1 Hz with a duration of 665 μs. Mode 2: on titanium inserts—arc-pulse frequency of 160 Hz with a duration of 50 μs, on molybdenum inserts—arc-pulse frequency of 20 Hz with a duration of 45 μs, on aluminium inserts—arc-pulse frequency of 1 Hz with a duration of 665 μs. Mode 3: on titanium inserts—arc-pulse frequency of 40 Hz with a duration of 50 μs, on molybdenum inserts—arc-pulse frequency of 200 Hz with a duration of 45 μs, on aluminium inserts—arc-pulse frequency of 2 Hz with a duration of 665 μs.

In these modes, coatings were obtained on samples with deposition duration of 20 minutes. The plasma-source operation mode in all cases was as follows: amplitude value of the vacuum arc discharge current—420 A, with the corresponding delay time between vacuum arc pulses for each mode. The delay time included the time for restoring the dielectric strength of the cathode–anode gap after a vacuum-arc discharge; the time required for the plasma of the ignition discharge to form the necessary charged particle density in the cathode–anode gap to initiate the main vacuum-arc discharge (approximately 40 μs), and the hold time between arc pulses to reduce thermal load on the cathode assembly [27].

Obtained coatings were analysed using a PEM-106 scanning electron microscope equipped with an energy-dispersive microanalysis system. The analysis results showed that the coating thickness on the samples was, on average: 2.4 μm in mode 1, 4.1 μm in mode 2, 6.7 μm in mode 3. The resulting component composition of the coatings for the studied modes is presented in Table 1.

Analysis of the data presented in Table 1 shows that, with the specified frequency and duration of vacuum arc pulses for each group of inserts of the same material, and with consistent timing and sequential activation of each insert group—and within each group, each individual insert—the composition of the resulting multicomponent coating is entirely determined by the frequency of arc pulses in each insert group. So, when an even rate of material evaporation from each group of inserts is maintained per unit time, the coating composition has equal component content (Table 1, mode 1). When the duration of operation (the number of activations per unit time) in the insert groups for a particular material is increased or decreased, the content of those materials in the coatings changes accordingly (Table 1, modes 2 and 3, respectively). Deviations from the specified coating composition within 5% in various modes in Table 1 are attributed to measurement error

TABLE 1. The specified and obtained content of the insert materials in the coatings at arc pulse frequencies f.

No experiment	Ti content		Mo content		Al content	
	Specified, %	Obtained, %	Specified, %	Obtained, %	Specified, %	Obtained, %
			Mode 1			
	$f = 40$ Hz		$f = 40$ Hz		$f = 1$ Hz	
1	33.4	31.9	33.3	34.2	33.3	31.9
2	33.4	34.1	33.3	32.4	33.3	34.4
3	33.4	32.6	33.3	32.8	33.3	32.2
			Mode 2			
	$f = 160$ Hz		$f = 20$ Hz		$f = 1$ Hz	
1	72.7	71.4	9.1	10.3	18.2	17.3
2	72.7	73.9	9.1	8.9	18.2	19.1
3	72.7	72.0	9.1	9.9	18.2	18.5
			Mode 3			
	$f = 40$ Hz		$f = 200$ Hz		$f = 2$ Hz	
1	12.5	12.1	62.5	61.6	25.0	24.2
2	12.5	12.8	62.5	62.3	25.0	26.1
3	12.5	11.7	62.5	63.7	25.0	25.6

in the component composition of the coating using the PEM-106 microscope and less than 100% reliability of vacuum arc initiating.

5. CONCLUSION

The design of a pulsed vacuum-arc plasma source with the composite cathode assembly was developed for obtaining multicomponent coatings. The use of a high-thermal-conductivity metal for the cathode base, with cylindrical inserts made of other metals (forming the coating composition) placed in the base holes uniformly along concentric circles relative to the base axis, enables effective cooling of cathode elements during plasma-source operation, allowing for high-quality multicomponent coatings. A manufacturing technique was developed to ensure the airtightness of the composite cathode.

The use of a separate arc igniting system on each insert, consisting of an insulator and an igniting electrode for excitation of the pulsed vacuum-arc discharge, significantly increases the service life of the pulsed plasma source (by a factor of N, where N is the number of inserts).

The experimental method was proposed to determine durations of vacuum arc pulses on inserts made of different materials to ensure ma-

terial deposition from only these inserts. The relationship between the content of a particular metal in the coating and parameters such as metal electron transport coefficients, the number of inserts, average arc current, arc pulse frequency for inserts of the same metal, and their operation time was demonstrated. The possibility of using the cathode base material as a component in the coating was also proven.

Practical tests of the pulsed plasma source with the composite cathode showed that the obtained coatings were of high quality. The plasma source itself demonstrated high service life with reliable excitation of the pulsed vacuum arc (vacuum-arc ignition probability close to 97%), and the composition of the obtained coatings was determined by the operation time of inserts made of different metals.

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