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PULSED VACUUM-ARC PLASMA SOURCE WITH LASER ARC EXCITATION

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A method of solution to the issue of contamination of the laser beam input window in pulsed vacuum-arc plasma sources with vacuum arc laser excitation is proposed. The method involves the periodic introduction of energy through an unfocused laser beam into a layer of condensate formed on the surface of the laser beam input window. The focus of such a cleansing laser beam is located outside the vacuum chamber, ensuring the absence of unauthorized activation of the plasma source, and the optical axis is perpendicular to the input window surface, providing optimal conditions for removing the formed condensate film. The periodicity of cleansing the laser beam input window, which determines the window throughput, is based on the condition of ensuring the probability of vacuum arc excitation not below a specified level. The area of the cleansing laser beam unfocusing spot S_{unf} on the laser beam input window surface facing the plasma source cathode is determined under the condition of ensuring the power density q of the laser radiation on the cleansed surface in the range of $10^4 \leq q \leq 10^5$ W/cm^2 and the condition $S_{unf} \geq S_{exc}$, where S_{exc} is the area of the laser beam spot that excites the vacuum arc discharge on the input window surface facing the plasma source cathode. The vacuum arc excitation in the pulsed plasma source using the proposed method, which allows removing the condensate layer on the laser beam input window, is characterized by a stable 95% probability of exciting the vacuum arc at a pulse repetition frequency of 300 Hz, regardless of the plasma source operating duration.

INTRODUCTION

Vacuum-arc coatings are widely used to enhance the functional capabilities of various products in many industrial sectors, including mechanical engineering, nuclear power, microelectronics, etc. [1–3]. These coatings are obtained in ion-plasma installations, where vacuum-arc plasma sources play a crucial role. They generate plasma streams from which coatings of the required composition are formed on workpieces [4, 5].

One of the key characteristics of vacuum-arc plasma sources is the number of microdroplets in the generated plasma stream. To prevent the deposition of microdroplets onto the substrate, which is crucial when producing coatings for use in optics and microelectronics, various designs of plasma filters are applied [6–8]. The use of such plasma filters significantly complicates the plasma source design and reduces the ion current onto the substrate, leading to a decrease in the productivity of the coating deposition process.

In many cases, to reduce the fraction of microdroplets in the generated plasma stream, so-called 'non-filtering methods' can be employed. These methods do not ensure high plasma purification from microdroplets but are much simpler and more cost-effective in comparison with techniques involving plasma filters [9]. Several 'non-filtering methods' are based on specific operating modes of the vacuum arc, which create plasma streams with low microdroplets content [6, 9].

One of these modes is the pulsed arc burning mode. In this mode, due to the short duration of the cathode spot staying in one place, the number of microdroplets in the plasma stream is significantly reduced [9], and this quantity can be regulated by the arc pulse duration [10, 11]. While plasma filters were previously used for depositing of pulsed plasma streams, they are practically not employed anymore [12]. Equipment for generating pulsed plasma streams is discussed in works [13, 14].

The reliability and operational duration of pulsed vacuum-arc plasma sources are significantly influenced by the vacuum arc ignition system. In this regard, laser systems for initiating vacuum-arc discharges are considered promising [15]. They have practically no limitations in terms of operational lifespan, ensuring reliable excitation of the vacuum arc. These systems exhibit a high degree of reproducibility of plasma parameters from pulse to pulse, while scanning the laser beam with its optical system over the cathode working surface or moving the cathode working surface, uniform wear is achieved. However, a complete solution to the issue of contamination of the laser beam input window in the vacuum chamber during the operation of pulsed plasma sources, which reduces their reliability, has not been achieved yet. Therefore, research in this direction remains relevant.

1. ANALYSIS OF THE ISSUE CURRENT STATE

Laser ignition of the vacuum arc is increasingly utilized in various types of plasma devices. Creating plasma in the interelectrode gap using a laser beam directed at one of the electrodes or directly in the gas is widely applied for arc ignition in controlled vacuum arresters [16, 17]. The advantages of this ignition method include high switching accuracy of the arrester, galvanic separation of ignition and main discharge circuits, and long service life [18]. To reduce the impact of contamination of the laser beam input window in these devices, the design complexity is increased by employing multistage arc ignition. Moreover, the operating frequency of vacuum arresters is not very high.

In plasma sources based on stationary arc discharge, this method has not yet found practical application because the mentioned advantages of laser arc ignition are not decisive in this case. Furthermore, there is an issue of contamination of the laser beam input window in the vacuum chamber, which remains unresolved [15].

The same issue exists in pulsed vacuum-arc plasma sources too. In modern plasma sources, this issue is primarily addressed by minimizing the amount of erosion products (especially material vapors) from the cathode that reach the laser beam input window. Examples of implementing this approach can be found in works [19, 20], where the input window is shielded and only briefly exposed when the radiation passes through.

In the pulsed plasma source with the laser-initiated arc investigated by Scheibe H.-J. et al. [21, 22], after approximately two seconds (1000 pulses) of operation of plasma source with a graphite cathode, due to the deposition of a carbon film, the transparency of the laser beam input window decreases by 60%, leading to a significant reduction in arc excitation reliability. To protect the laser beam input window from contamination, a more radical approach was employed – completely closing the path of material vapor flow from the cathode to the input window. To achieve this, a strip of transparent polymer material is placed in front of it, moving across the window during the source operation, continuously renewing the transparency of the radiation input channel [23].

The solutions proposed in the works [19–23] for protecting the laser beam input window from contamination are not perfect, as they significantly complicate the design of the ignition system and the plasma source itself, increasing its cost and significantly reducing its reliability. Moreover, solutions aimed at minimizing the contamination of the input window [20] still require periodic cleansing or replacement of the laser beam input window.

Possible solutions to the issue of contamination of the laser beam input window during the vacuum arc initiation have been analyzed in the work [15]. The method of maintaining the substrate temperature no lower than a certain critical temperature, depending on the vapor flow density and at which the metal vapor condensation does not occur on any targets [24], was deemed impractical. The reason is that maintaining the laser beam input window temperature at a level where condensation does not occur (usually above 1000 K) is practically impossible.

In this case, it is possible to introduce energy into the condensation zone either into a very thin surface layer of the laser beam input window, onto which cathode material molecules deposit, or directly into the forming condensate layer. This energy can be introduced by known methods – microwave radiation, electron beam, or laser radiation. According to the authors of the work [15], the most promising method is introducing energy using a laser beam. However, its implementation requires further research, as it is necessary to consider the peculiarities of thin films formation [1–4, 25], as well as various other factors – the plasma source cathode material, the current of the vacuum-arc discharge, the power of the introduced energy, the method of introduction (including pulsed or steady-state), etc.

2. RESEARCH TASKS AND OBJECTIVE

The objective of this study is to develop a pulsed vacuum-arc plasma generator with laser arc excitation, incorporating a novel ignition system. The applied ignition system, besides its primary function of the vacuum arc excitation, also serves for removing the film that condenses on the laser beam input window. The removal of this film is achieved using an auxiliary laser beam. The research tasks of the study include investigating the operating conditions of the proposed ignition system to ensure the reliable operation of the plasma source.

3. RESULTS AND THEIR DISCUSSION

3.1. DESIGN OF PULSED PLASMA SOURCE WITH LASER ARC EXCITATION

In developing the design of the pulsed plasma source with a novel laser ignition system, the foundation was laid by a pulsed plasma generator described in the work [21]. What sets apart the created pulsed plasma source is the utilization of two laser beams in the laser ignition system. The primary beam initiates the vacuum arc and an auxiliary one cleanses the laser beam input window from the cathode material condensate. The schematic representation of the developed pulsed plasma source with the novel laser ignition system is shown in Fig. 1.

The pulsed plasma generator is located inside a vacuum chamber 1, which is evacuated to a working pressure of about 10^{-3} Pa. Its main components – a rod-shaped anode 2 and a flat cathode 3 – are made from АГ-1500 grade carbon [5]. The voltage supplied to the device electrodes is provided from the power supply line (not shown in Fig. 1). To ensure uniform wear of the cathode, its movement along mutually perpendicular X and Y coordinates is organized (using stepper motors).

Excitation of the vacuum-arc discharge in the plasma generator is achieved by the pulse of the beam 7 of the laser 14, which passes through a long-focus lens 8, the input window 9, and focuses on the cathode surface near the edge of the anode. On the cathode surface where the laser beam strikes, a cathode spot 4 of the vacuum arc is formed. This cathode spot creates a plasma flow 5, which falls on the substrate 6, forming a coating of cathode material on it.

To generate laser radiation pulses, an Nd-YAG laser was utilized [26]. In our case, it operated with the following parameters: $\lambda = 1.06$ μm, pulse energy – 6 mJ, pulse frequency – 300 Hz, peak power – 67 kW. The focused laser beam spot on the cathode surface had the following characteristics: spot diameter – 150 μm, power density within the spot – $3.8 \cdot 10^{8}$ W/cm².

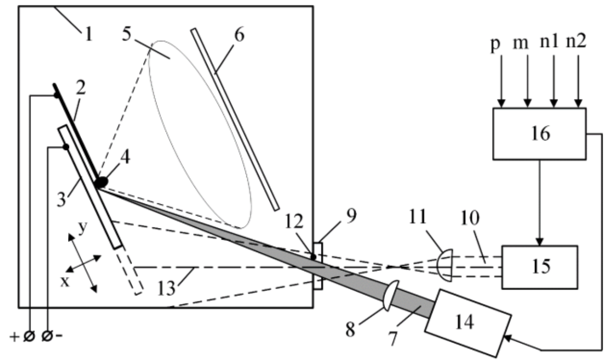

Fig. 1. Design of the developed pulsed plasma source with laser ignition system:
1 – vacuum chamber; 2 – anode; 3 – movable cathode; 4 – cathode spot of the vacuum arc; 5 – plasma cluster created by the cathode spot; 6 – substrate; 7 – laser beam initiating the vacuum arc; 8 – optical system focusing the initiating laser beam on the cathode; 9 – laser beam input window; 10 – auxiliary laser beam; 11 – optical system unfocusing the auxiliary laser beam; 12 – side of the input window where the cathode material condenses; 13 – optical axis of the auxiliary laser beam; 14 – main laser; 15 – auxiliary laser; 16 – control unit

For cleansing the surface 12 of the input window 9, a laser beam 10 generated by the laser 15 is used, with its optical axis 13 perpendicular to the surface of the input window 9. This laser beam 10 passes through a short-focus lens 11, the focus of which is located outside the vacuum chamber 1.

The lasers operation is regulated by the control unit 16, which receives information about the pressure in the vacuum chamber *p*, the cathode material *m*, the number of required activations of the pulsed plasma source (pulses of the vacuum-arc discharge) *n1*, and the number of activations of the pulsed plasma source in the current technological process *n2*.

3.2. PRINCIPLES OF OPERATION OF THE LASER ARC EXCITATION SYSTEM WITH LASER BEAM INPUT WINDOW CLEANSING

The main distinction of the developed pulsed plasma generator, which initiates the vacuum-arc discharge using a laser beam, from similar systems utilizing the same method of exciting the vacuum arc, lies in the use of an additional laser beam. This additional laser beam serves the function of cleansing the surface of the input window from the cathode material that condenses on it. Therefore, we will consider the operational specifics of this excitation system.

The cause-and-effect relationship between the increase in the film formed on the surface of the input window and the probability (reliability) of the vacuum arc excitation during its initiation by a laser beam can be presented as follows: formation and growth of the film on the input window → loss of transparency of the input window → decrease in the energy of the laser beam initiating the vacuum arc → reduction in the probability of the vacuum arc excitation to unacceptable levels (usually less than 50%). This final link in the chain, in fact, leads to a decrease in the reliability of the pulsed vacuum-arc plasma generator operation.

To deposit 1 nm of material on the substrate, 150 pulses of the vacuum arc are required for carbon and 400 ones for titanium in the operation of a similar device [23]. Consequently, for one arc pulse, the deposition on the substrate results in a thickness of $6.7 \cdot 10^{-3}$ nm in the case of a carbon cathode and $2.5 \cdot 10^{-3}$ nm in the case of a titanium cathode. These values are smaller than the size of both a carbon atom ($7.7 \cdot 10^{-2}$ nm) and a titanium atom ($14.6 \cdot 10^{-2}$ nm) [27]. Similar deposition rates will occur on the surface of the laser beam input window, which is typically located at a comparable distance from the source of the deposited cathode material (cathode spot of the arc).

It is evident that the presence of an extremely small volume of cathode material condensed on the surface of the input window after one pulse of the vacuum arc will not lead to a significant reduction in the probability of the arc ignition with the next laser pulse. Hence, to ensure the necessary transparency of the input window for high-probability arc ignition with the laser beam initiating the arc, periodic cleansing can be applied. For instance, by setting an acceptable single atomic layer coating thickness on the input window surface, at which the reduction in the probability of arc excitation practically does not occur (since at this stage of condensation, an island structure forms instead of a monolayer) [28], the periodicity of cleansing with an additional laser beam would be one cleansing cycle for every 12 ignitions of the vacuum arc in the plasma generator in the case of a carbon cathode and approximately 59 arc ignitions for a titanium cathode.

In general, the periodicity of the input window cleansing from the cathode material film formed on it until the moment of cleansing depends on the cathode material (its electron transfer coefficient), the distance from the location of the cathode spot of the vacuum arc (the source of cathode erosion products) to the input window, the duration of the arc discharge pulse, and the current in it. Also, it is determined by the accepted level of allowable reduction in the input window transparency until the moment of cleansing, at which the specified probability (reliability) of the vacuum arc excitation is ensured.

When choosing the cleansing frequency of the input window in the developed plasma source, the following factors were taken into account. Firstly, in the operation of the pulsed plasma generator with a similar geometry, 1000 ignitions lead to a 60% reduction in the input window transparency and a corresponding decrease in the arc excitation probability. Secondly, the first-order approximation was taken as the basis for the linear relationship between the reduction in the input window transparency and the carbon film thickness formed on it. Thirdly, the permissible reduction in the input window transparency was set at no more than 10% (ensuring a probability of arc excitation of approximately 90%).

Given these circumstances, for our specific case of the plasma pulsed source design with a carbon cathode, at an arc current amplitude of 450 A and an arc pulse duration of 40 μs, the cleansing frequency of the input window was determined at the level of one cleansing pulse per 100 vacuum arc ignition pulses.

The choice of the arrangement scheme for the additional laser beam cleansing the film on the input window (see Fig. 1) was made based on the following considerations.

The input window cleansing from the condensed film is performed in the developed device using an unfocused laser beam, the focus of which is located outside the vacuum chamber. In this arrangement, firstly, unfocusing of the laser beam allows ensuring the necessary cleansing area of the input window Scl, which should not be less than the area of the input window zone through which the initiating laser beam is introduced, ensuring the excitation of the arc discharge Sin. Secondly, the use of a laser beam with a focus located outside the vacuum chamber eliminates the impact of the focused zone of this beam on the structural elements inside the vacuum chamber and the possible occurrence of unipolar arcs on them, ensuring the formation of coatings on the substrate without impurities from the material of these structural elements.

The area of the unfocused laser beam cleansing spot S_{cl} on the surface of the laser beam input window, directed towards the cathode of the plasma source, was determined not only by the condition $S_{cl} \geq S_{in}$ but also by the condition of ensuring the laser radiation power density q on the cleansed surface in the range of $10^4 \leq q \leq 10^5$ W/cm^2.

The laser radiation power density q on the cleansed surface should be such that it ensures a mechanism of shock-mechanical cleansing (Fig. 2), which is realized at the laser radiation power density q in the range of $10^4…10^5$ W/cm^2 [29]. At lower power density q introduced into the film (the case when $q < 10^4$ W/cm^2), only thermal heating of the formed film on the cleansed surface will occur without its removal. In the case when $q > 10^5$ W/cm^2, film removal will occur through the vaporization mechanism of laser cleansing. However, in case of implementing the vaporization mechanism, the temperature of the film can reach several thousand Kelvins. Since this film is located on the surface of the laser beam input window (made of a fragile material like glass), localized overheating of this surface with its subsequent destruction is possible.

In general, the laser radiation power density q on the surface, where the laser radiation falls, depends on the beam contact area with the surface, the energy E in the laser radiation pulse, and its duration τ. For example, in the laser operating mode with an energy in the pulse E = 6 mJ and a peak power P = 40 kW with a focal spot area $S = 17.7 \cdot 10^{-5}$ cm^2 the power density $q = 2.3 \cdot 10^8$ W/cm^2 is introduced on the surface layer of the cathode (initiation mode of the vacuum arc), leading to the formation of a plasma cloud.

To achieve $q = 1 \cdot 10^5$ W/cm^2 (laser cleansing mode) under the same laser operating conditions, it is necessary to determine the area of the laser beam unfocusing spot S_{unf} on the cleansed surface, which is equal to 0.4 cm^2.

Creating the required laser radiation power density q on the cleansed surface by changing the area of the laser beam unfocusing spot S_{unf} is a simple operation. It can be accomplished by either replacing the focusing lens with a lens of the necessary focal length or by moving the lens along its optical axis.

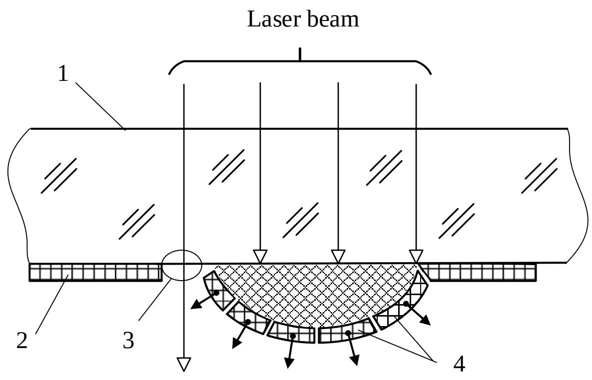

Fig. 2. Mechanism of shock-mechanical cleansing of the input window surface from the film: 1 – laser beam input window; 2 – film (film islands) located on the input window surface; 3 – area of the input window surface free from film islands; 4 – fragments of the destroyed film

The developed pulsed vacuum-arc plasma source was used to obtain diamond-like carbon (DLC) films on stainless steel samples with a thickness of about 1 μm. This was achieved through $1.6 \cdot 10^5$ activations of the device at a vacuum arc pulses excitation frequency of 300 Hz. During the pulsed plasma source operation every 100 arc activations one laser pulse from the auxiliary laser was applied to cleanse the input window from the film that had formed on it up to that point. The laser cleansing system design is based on the principles mentioned above. This ensured a constant level of vacuum arc excitation probability in the pulsed plasma source during the DLC film deposition process, reaching close to 95% both at the beginning and at the end of the deposition process.

CONCLUSIONS

The paper describes the design of the pulsed vacuum-arc plasma source with a novel method of vacuum arc excitation using laser radiation. This plasma source not only initiates the arc with a laser beam but also cleanses the input window surface from the film made of cathode material using auxiliary laser radiation.

The conducted analysis of the conditions ensuring effective cleansing of the input window allowed determining the principles of operation for the laser arc excitation system with laser beam input window cleansing.

The results of the operation of the pulsed vacuum-arc plasma source with a novel type of vacuum arc excitation system during the production of DLC coatings showed that the laser beam input window transparency does not decrease throughout the entire coating deposition cycle. This is evidenced by the high probability of a vacuum arc excitation in the pulsed plasma source, which remains constant, close to 95%, both at the beginning and at the end of the deposition process.

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ІМПУЛЬСНЕ ВАКУУМНО-ДУГОВЕ ДЖЕРЕЛО ПЛАЗМИ З ЛАЗЕРНИМ ЗБУДЖЕННЯМ ДУГИ

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Запропоновано метод вирішення проблеми запилення вікна введення лазерного випромінювання в імпульсних вакуумно-дугових джерелах плазми з лазерним підпалюванням дуги. Метод полягає у періодичному введенні енергії розфокусованим променем лазера у шар конденсату, який формується на поверхні вікна введення лазерного випромінювання. Фокус такого очищувального променю лазера знаходиться поза вакуумною камерою, що гарантує відсутність несанкціонованого спрацювання джерела плазми, а оптична вісь перпендикулярна до поверхні вікна введення, що забезпечує кращі умови для видалення сформованої плівки конденсату. Періодичність очищення вікна введення лазерного випромінювання, яка визначає пропускну здатність вікна введення лазерного випромінювання, знаходиться із умови забезпечення ймовірності збудження вакуумної дуги не нижче заданого рівня, а площа плями розфокусування $S_{роз}$ очищувального променю лазера на поверхні вікна введення лазерного випромінювання, зверненій до катода джерела плазми, визначається за умови забезпечення щільності потужності q лазерного випромінювання на поверхні, що очищується, у діапазоні $10^4 \leq q \leq 10^5$ Вт/см^2 та умови $S_{роз} \geq S_{збуд}$, де $S_{збуд}$ – площа плями лазерного випромінювання, що збуджує вакуумний дуговий розряд, на поверхні вікна введення, зверненій до катода джерела плазми. Ініціювання вакуумної дуги в імпульсному джерелі плазми за допомогою запропонованого методу, який дозволяє видаляти шар конденсату на вікні введення лазерного випромінювання, характеризується стабільною ймовірністю збудження вакуумної дуги на рівні 95% при частоті прямування імпульсів дуги 300 Гц незалежно від тривалості роботи джерела плазми.