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SYSTEM FOR MEASUREMENT THE PRODUCT SURFACE TEMPERATURE FOR VACUUM-ARC COATINGS

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The developed system for measuring the surface temperature of products using the pyrometric method is described. Its application in obtaining vacuum-arc coatings improves their quality. The system differs from known analogs by its operational reliability, high accuracy of surface temperature measurement of processed products, and the ability to perform measurements both during ion cleaning of the surface and during the coating process. The distinctive features of its operation lie, firstly, in the fact that the opening of the shutter-screen of the pyrometer input window occurs after the plasma source is turned off, with a delay ensuring the absence of contamination on the pyrometer input window. Secondly, the temperature measurement process takes place while the sample product is positioned at the temperature measurement point, with the movement of the processed products halted in the vacuum chamber. Based on the results of temperature monitoring, the voltage supplied to the products is adjusted. The practical testing of the developed temperature measurement system during the coating process on drills made from P6M5 high-speed steel in the modernized "Bulat-6" installation demonstrated that they have 1.7 times greater wear resistance compared to similar drills coated with titanium nitride using traditional technology when processing Ст45 steel.

INTRODUCTION

In a number of technological processes for obtaining vacuum-arc coatings on various products, both the input of radiation into the vacuum chamber (e.g., a laser beam for initiating a pulsed vacuum arc [1, 2]) and its output (e.g., infrared radiation from the surface of processed products for temperature control using a pyrometer [3, 4]) are utilized. This necessity also arises during optical diagnostics of plasma [5].

In all such cases, the challenge arises of protecting the input-output radiation window of the vacuum chamber from the erosion products of the plasma source cathode. This issue remains unresolved to date, leading to a significant reduction in the efficiency of processes that involve various types of radiation. Thus, according to [6], during the excitation of a vacuum arc with a laser beam focused on the graphite cathode of a pulsed plasma source, the transparency of the laser radiation input window decreases by 60% after approximately two seconds of source operation due to the deposition of a carbon film. This substantially reduces the efficiency of arc excitation.

The same problem occurs when infrared (thermal) radiation is output from the surface of processed products to the pyrometer measuring sensor during ion-plasma coating deposition processes [4], which decreases the accuracy of product temperature control and, consequently, the quality of the coatings. Known protective measures against the condensation of plasma particles on the input-output radiation window, as a rule, only partially address this issue. Therefore, finding effective solutions to this problem remains highly relevant.

1. ANALYSIS OF THE ISSUE STATE

Protection of the laser radiation input window in the vacuum chamber from contamination is mainly addressed in modern plasma sources by minimizing the amount of cathode erosion products (primarily material vapors) that reach the input window. Examples of this approach can be found in studies [7, 8], where the input window is shielded by a shutter that opens only briefly during the passage of radiation. This solution undoubtedly reduces the amount of cathode material deposited on the input window; however, it cannot completely eliminate contamination of the input window.

The laser beam input window protection used in a pulsed plasma source with laser-initiated arcs by Scheibe H.-J. et al. [1, 2] is more radical. A similar solution is employed in one of the plasma source variants described in [7]. In these designs, the vapor flow path from the cathode material to the input window is completely blocked. This is achieved by placing a transparent polymer screen in front of the window, which moves continuously during operation, constantly renewing the transparency of the radiation input window. However, this approach significantly complicates the plasma source design and requires periodic replacement of the screen after a certain operational period.

To eliminate distortions in the spectrometer readings, the input-output radiation window in [5] was fully closed with a shield, and the radiation was directed to the spectrometer through a thin stainless-steel tube with a diameter of 2.6 mm and a length of 20 cm, embedded in the shield. The tube was positioned 18 cm away from the target surface at an angle of 60° to the normal. This design reduces the contamination of the spectrometer input window, as the particles from the sputtered target enter the long, narrow tube from a small area of the target. However, it cannot completely eliminate contamination of the input window.

The solutions proposed in [1–3, 6–8] to protect the input-output radiation window from contamination are not perfect, as they significantly complicate the design of vacuum coating deposition systems. Furthermore, these approaches to minimizing window contamination

still require periodic cleaning or replacement of the window.

The method of addressing the problem of the input-output radiation window contamination by maintaining its temperature above a certain critical value determined by the vapor flux density and at which metal vapor condensation does not occur on any targets [9] was analyzed in [10]. The reason this method is infeasible lies in the difficulty of maintaining the window temperature at a sufficiently high level (no less than the melting point of refractory metals, which are typically used in vacuum-arc technologies). Furthermore, the windows themselves are made of various types of glass, the most heat-resistant being quartz glass, which can withstand temperatures of up to 1100 °C (short-term exposure up to 1400…1500 °C), which is still below the required lev-el.

A solution to this issue, in most cases when obtaining vacuum-arc coatings, could be the method for cleaning the laser radiation input window into the vacuum chamber proposed in [11]. The method involves periodic introducing energy through an unfocused laser beam into a layer of condensate formed on the surface of the input window. The periodicity of cleaning the laser radiation input window, which determines the window throughput, is established to ensure the probability of vacuum arc excitation not below a specified level. The area of the cleaning laser beam unfocusing spot S_{unf} on the input window surface facing the vacuum chamber is determined from the condition of ensuring the laser radiation power density q on the cleansed surface within the range of $10^4 \le q \le 10^5$ W/cm^2. Using this method to initiate a vacuum arc in a pulsed plasma source allows removing the condensate layer on the laser radiation input window and ensures a stable vacuum arc excitation probability at 95% with an arc pulse frequency of 300 Hz, regardless of the plasma source operating duration. However, applying this method when measuring the surface temperature of products using a pyrometric method during vacuum-arc coating processes proves to be very challenging.

The aim of the article is to develop a system for measurement the surface temperature of products in vacuum-arc coating processes using the pyrometric method. The principle of its operation ensures the complete absence of cathode erosion products entering on the infrared radiation output window of the pyrometer measuring sensor.

2. SYSTEM FOR MEASUREMENT THE SURFACE TEMPERATURE OF PRODUCTS IN VACUUM-ARC COATING PROCESSES

The surface temperature of products during vacuum-arc coating deposition was measured using a system which structural diagram is shown in Fig. 1. This system was developed on the basis of the "Bulat-6" installation.

The following components are directly related to the system for measurement the surface temperature of the processed products: pyrometer 1 of the OPTRIS CTlaser LT series CF2 optics 75:1 type [12], which sensor receives infrared radiation 2 from the product 3. The next components are situated along the path of this radiation; a shutter-screen 5, which is opened by an electromagnet 6 and an actuator rod 7; a window 4, and a control unit 8, which receives a product temperature signal from the pyrometer. The remaining elements shown in Fig. 1 are intended for the deposition of coatings on the processed products using the ion-plasma method [13].

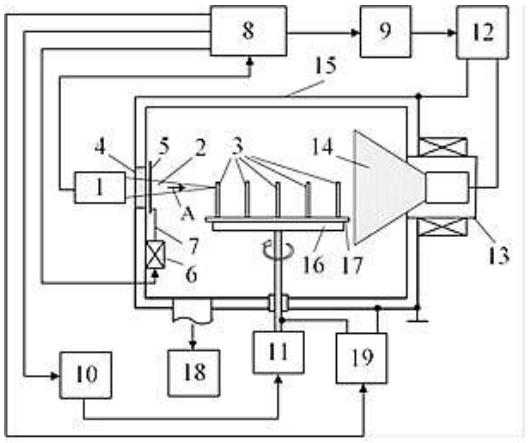

Fig. 1. Structural diagram of the system for measurement the surface temperature of products during vacuum-arc coating deposition: 1 – pyrometer; 2 – infrared radiation; 3 – products; 4 – radiation output window; 5 – shutter-screen; 6 – electromagnet; 7 – actuator rod; 8 – control unit; 9 – vacuum arc excitation-extinguishing unit; 10 – stepper drive controller; 11 – stepper drive; 12 – plasma source power supply unit; 13 – plasma source; 14 – plasma flow; 15 – vacuum chamber; 16 – planetary mechanism; 17 – substrate holder; 18 – evacuation system; 19 – bias voltage source

The control unit, based on its programmed algorithm, ensures the process of measuring the temperature of the products at various stages of coating deposition. It manages its output signals to control other units as follows. Before measuring the products temperature, the power supply unit 12 of the plasma source 13 is turned off using the vacuum arc excitation-extinguishing unit 9, halting the formation of the plasma flow 14. Simultaneously, the rotation of the planetary mechanism 16 and the substrate holder 17 with the secured products, is stopped. This ensures that the sample product, which surface temperature is to be measured, is positioned precisely at the measurement point, as shown in Figs. 1 and 2. Subsequently, after a delay of several milliseconds, the shutter-screen is opened, the temperature of the sample product is measured, the shutter-screen is closed, and the coating deposition process continues until the next temperature measurement cycle.

Based on the results obtained during the measuring the product temperature, the control unit issues an appropriate control signal to the bias voltage source 19, which increases or decreases the voltage applied to the processed products. This enables product temperature monitoring during the coating process, allowing the temperature of the products to be maintained at the level required to achieve high-quality coatings by increasing or decreasing the voltage supplied to them.

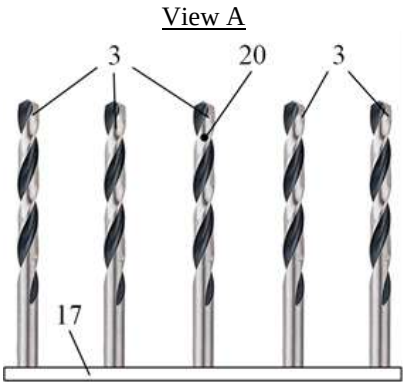

Fig. 2. Location of the pyrometer measuring spot on the processed product surface when positioned at the temperature measurement point (see view A, Fig. 1): 20 – location of the pyrometer measuring spot on the processed product surface at the temperature measurement point; other designations are as in Fig. 1

3. FEATURES OF THE TEMPERATURE MEASUREMENT SYSTEM OPERATION

The main features of the developed system for measurement the temperature of products during the process of obtaining vacuum-arc coatings, which ensure high measurement accuracy, are as follows. The first feature is that the opening of the shutter-screen occurs after the plasma generation is stopped, with a delay that ensures the absence of plasma particles in the working volume of the vacuum chamber. The second feature is that the temperature measurement process is carried out when the processed product is positioned at the temperature measurement point, with the movement of the processed products in the vacuum chamber stopped.

3.1. DELAY TIME FOR SHUTTER-SCREEN OPENING

After the plasma source ceases operation, plasma particle generation stops, and no new particles will enter the vacuum chamber. However, a certain delay time is required to allow the particles present in the vacuum chamber at the moment the plasma source stops to condense onto the surfaces of the structures inside the vacuum chamber. This ensures the complete absence of contamination of the pyrometer optical system input window.

The delay time is determined by the speed of restoring the vacuum dielectric strength after the discharge is terminated (i.e., the time of plasma deionization and the deposition of its particles on the structural elements inside the vacuum chamber), which usually does not exceed several tens of microseconds [14]. However, studies [15] show that the density of the neutral vapor in the vacuum chamber, which follows the quenching of a high-current (2…11 kA) vacuum arc between copper electrodes, de-creases at least one order of magnitude more slowly than expected. Such results can be explained if it is assumed that the cathode material vapor is formed by the evaporation from molten droplets that were ejected from the arc cathode spots before the discharge was interrupted. Based on this, it can be assumed that the delay time of several milliseconds for opening the shutter-screen will ensure the complete absence of cathode material particles in the vacuum chamber by the time of the temperature measuring. This, in turn, guarantees the absence of unwanted contamination on the input window of the pyrometer optical system, thereby ensuring high accuracy in measuring the products surface temperature during the coating processes.

An additional positive result of this solution is that the temperature of the processed product surface is measured in the absence of plasma in the working volume of the vacuum chamber. The absence of radiation from the plasma in this case further enhances the accuracy of the temperature measuring of the processed product surfaces.

3.2. TEMPERATURE MEASUREMENT POINT

The most accurate temperature measurement with a pyrometer is achieved when its measurement spot is at least twice as small as the measured object [16]. In general, meeting this requirement during the continuous rotation of processed parts in a vacuum chamber is only possible when the processed part, whose surface temperature is being measured, is located at the temperature measurement point while the movement of the processed parts in the vacuum chamber is stopped.

The temperature measurement point is the location of the processed product where the requirement is met that the pyrometer measurement spot on the product surface is at least twice as small as the measured object (product). For example, when applying hardening coatings to drills with a diameter of 6 mm and measuring their temperature, the pyrometer measurement spot on the drill surface should not exceed 3 mm. To ensure this, a pyrometer must be used that allows achieving the required measurement spot diameter at a given distance between the pyrometer and the product surface. For instance, in the case of processing drills with a diameter of 6 mm, the OPTRIS CTlaser LT series CF2 optics 75:1 pyrometer [12] can be used, which provides a measurement spot diameter of 1.9 mm at a distance of 150 mm.

The processed products in a vacuum chamber typically rotate both around their own axis and around the axis of the substrate holder using a planetary mechanism on which they are mounted. The rotation speed, for example, in “Bulat” installations, is 8 rpm [17]. At this speed, the linear velocity of processed products at a radius of 200 mm (where the products can be mounted) is approximately 167 mm/s. During this time, when measuring temperature (the temperature measurement time with the high-speed pyrometer OPTRIS CTlaser LT is 9 ms, while typical measurement times are several tens of milliseconds), the product, which surface temperature is being measured, will move a distance of several millimeters (about 1.6 mm for a 9 ms measurement time). Such displacement, in the case of processing products with small diameters, will cause the pyrometer measurement spot to shift across the product surface, potentially even moving outside it, leading to significant temperature measurement errors. To prevent such errors, product surface temperature measuring must be performed precisely at the temperature measurement point when the movement of the processed products in the vacuum chamber is stopped.

To ensure products temperature measuring precisely at the measurement point, the following measures were applied. First, the stepper motor operating frequency was set lower than its responsiveness frequency (for example, for the used stepper motor ШД-5ДМ1, with a responsiveness frequency of 2800 Hz, the operating frequency was set to 800 Hz), ensuring no pulse skips during operation [18]. Second, a specially designed and manufactured planetary mechanism was used, in which the satellites complete a whole number of rotations per single revolution of the mechanism [19]. The use of such a planetary mechanism as a substrate holder guarantees that the processed product mounted on the satellite returns to the same initial position after each 360-degree rotation of the substrate holder. This ensures that a product initially positioned at the measurement point is precisely repositioned to the same location after each full rotation of the substrate holder, allowing temperature measurement of the same product surface area. These measures ensure high accuracy in temperature measurement of the products.

3.3. PRACTICAL TESTING OF THE TEMPERATURE MEASURING DEVICE

The products prepared for coating (drills made of high-speed steel P6M5 with a diameter of 8 mm) were placed on the substrate holder in the vacuum chamber. After that, the temperature measurement point was set on one of the processed products, selected as a reference sample for monitoring the surface temperature. The distance between the sensor of the applied pyrometer OPTRIS CTlaser LT(CF2) and the temperature measurement point was pre-adjusted to 150 mm, ensuring a measurement zone of 1.9 mm. Since the processed products are identical and under the same conditions, the surface temperature at the same point on each of them will be identical. The temperature measurement point 20 (see Fig. 2) was set on one of the processed products using the switched on dual-beam laser pointer of the pyrometer while the shutter-screen 5 was opened. This was done by moving the product around the axis of the substrate holder with the help of the stepper drive 11, controlled by controller 10, which operates in a stepwise control mode. The product was then rotated around its own axis. After setting the measurement point, the sample product was fixed in the substrate holder, and the shutter-screen was closed. The correct positioning of the temperature measurement point on the surface of the sample product 20 is shown in Fig. 2. The use of the developed planetary mechanism 17 ensured that, after each full rotation of the substrate holder, the sample product was precisely repositioned at the temperature measurement point based on a signal from the control unit.

The next step in obtaining coatings on the products was evacuating the vacuum chamber 15 to the operating pressure using the evacuation system 18. Once the required pressure was reached (typically $(1…5)\cdot10^{-3}$ Pa), the coating was applied to the products in two stages.

In the first stage, ion cleaning of the product surfaces was performed by applying a high voltage to the processed products (1200 V from the bias voltage source 19) while the plasma source was active. The standard plasma source of the “Bulat-6” installation, equipped with a titanium BT-1-1 cathode, was used for this process. Additionally, the products placed on the substrate holder were moved using a stepper drive. During the ion cleaning stage, the surface of the products is cleaned and heated to the required temperature. This heating is beneficial, as it ensures strong adhesion of the coating to the base. However, the surface temperature of the products must not exceed the hardening (tempering) temperature of the product base (for high-speed steel P6M5, this is 500…550 °C [20, 21]), as exceeding this limit would reduce the service life of the processed products.

At this stage of processing, the temperature of the products was monitored every 15 s using a pyrometer, which transmitted the temperature readings to the control unit as follows. After voltage was applied to the substrate holder with the processed products and the plasma source and stepper drive were simultaneously activated by the control unit, the unit sequentially sent two pulses to the stepper drive controller. For each control pulse, the controller ensured the operation of the stepper drive for the duration of exactly one full rotation of the substrate holder. The rotation speed of the substrate holder was 8 rpm, meaning that two rotations took 15 s. After this period, the substrate holder stopped, positioning the sample product at the temperature measurement point 20 (see Fig. 2).

Next, the surface temperature of the products was measured through the following actions executed by the control unit. The vacuum-arc discharge in the plasma source was stopped using the vacuum arc excitation-extinguishing unit. After stopping the coating particle generation process in the plasma source, a 10 ms delay was introduced to ensure that no residual particles remained in the vacuum chamber that could contaminate the optical window of the pyrometer. Following this delay, the shutter-screen was opened by applying a voltage pulse from the control unit 8 to the electromagnet 6, and the surface temperature of the products was measured.

The total time for temperature measuring after stopping the substrate holder was 93 ms, broken down as follows:

10 ms – delay before opening the shutter-screen;

37 ms – time required to open the shutter-screen;

9 ms – pyrometer temperature measurement time;

37 ms – time required to close the shutter-screen.

After each temperature measuring, a 5-s pause was introduced to allow heat to distribute deeper into the products. Once this pause ended, the ion cleaning process resumed, with the plasma source and the stepper drive of the substrate holder being reactivated simultaneously according to commands from the control unit.

Thus, during the ion cleaning process, continuous monitoring the surface temperature of the processed products was performed using a pyrometer. This monitoring continued until the surface temperature of the products reached 490 °C, which occurred after 2.5 min of ion cleaning. This indicated that the products were prepared for coating application, prompting the transition to the second stage – the coating deposition stage – conducted as follows.

With the plasma source operating and the substrate holder rotating, the control unit reduced the voltage applied to the products from the bias voltage source to 150 V. The gas inlet system (see not shown in Fig. 1) was then activated, introducing nitrogen (the reactive gas) into the vacuum chamber, increasing the chamber pressure to 10^{-1} Pa. Subsequently, the coating deposition process was carried out.

During the coating deposition process, surface temperature monitoring of the processed products was carried out in the same manner as at the ion cleaning stage. However, at this stage, temperature control was performed every 30 s. If, at any measurement, the surface temperature of the sample product was below 490 °C, the control unit sent a signal to the bias voltage source, increasing the voltage applied to the products by 20 V, thereby raising their temperature. Conversely, if the temperature exceeded 490 °C, the voltage was reduced by 20 V to lower the product temperature. These adjustments ensured the most favorable conditions for obtaining high-quality coatings. In this case, the coating deposition time was 20 min, resulting in a coating thickness of 3 μm.

Tests were conducted on four batches, each containing eight high-speed steel P6M5 drills with a diameter of 8 mm. The titanium nitride coating on these drills was applied using the proposed method of measurement the surface temperature of products during vacuum coating processes. The results of these tests showed that the coated drills exhibited 1.7 times greater wear resistance compared to identical drills coated with titanium nitride using the conventional technology when processing Ст45 steel.

The improvement in the functional characteristics of the processed products indicates that using this temperature measurement method – continuous monitoring of the product temperature during ion cleaning (which prevents overheating beyond the tempering temperature) and coating deposition – enables adjustments to the technological process parameters based on this monitoring. As a result, it enhances the quality of coatings obtained through the vacuum-arc deposition method.

During the tests, the delayed opening of the shutter-screen for surface temperature measuring after stopping the particle generation process ensured that no metal vapor particles were present in the vacuum chamber at the moment of measurement. As a result, there was no contamination of the input window of the pyrometer optical system. This, in turn, provided high accuracy in measuring the surface temperature of the products.

CONCLUSIONS

1. A system for measurement the surface temperature of processed products using the pyrometric method has been proposed, developed, and tested. Its application in vacuum-arc coating processes improves coating quality. The system is characterized by stability, accuracy, and reproducibility of temperature measurement results. This is ensured by protecting the pyrometer optics from condensation of cathode erosion products by turning off the plasma source, stopping product rotation in the vacuum chamber, and performing temperature measurements with a delay after turning off the plasma source.

2. The temperature measurement process is carried out at each stage of obtaining vacuum-arc coating – both during ion cleaning and coating deposition. Monitoring the products temperature allows for the timely completion of the ion cleaning process without tempering the product material and ensures that the product temperature is maintained at the specified level during coating deposition by adjusting the applied voltage. These measures contribute to obtaining high-quality coatings.

3. The high metrological characteristics of the developed system are achieved by ensuring that temperature measurements are always conducted under identical conditions – when the product is stationary at the designated temperature measurement point, which is set during system calibration. The precise positioning of the product at the measurement point after each full rotation of the substrate holder is achieved through the operation mode of the stepper motor and the use of a specially designed planetary mechanism of the substrate holder.

4. Tests were conducted on processed drills made of high-speed steel P6M5 with a diameter of 8 mm, which were coated with titanium nitride using the developed surface temperature measurement system. The results of these tests showed that the drills exhibited 1.7 times greater wear resistance compared to similar drills coated with titanium nitride using the traditional technology when processing Ст45 steel.

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СИСТЕМА ВИМІРЮВАННЯ ТЕМПЕРАТУРИ ПОВЕРХНІ ВИРОБІВ ДЛЯ ОТРИМАННЯ ВАКУУМНО-ДУГОВИХ ПОКРИТТІВ

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Описано розроблену систему вимірювання температури поверхні виробів пірометричним методом, застосування якої при отриманні вакуумно-дугових покриттів підвищує їх якість. Система відрізняється від відомих надійністю роботи, високою точністю вимірювання температури поверхні оброблюваних виробів, здійсненням вимірювання як при іонному очищенні поверхні, так і при нанесенні покриттів. Особливості її роботи складаються, по-перше, у тому, що відкриття заслінки-екрана вхідного вікна пірометра здійснюється після припинення роботи джерела плазми з затримкою, яка забезпечує відсутність запилення вхідного вікна пірометра, а по-друге, процес вимірювання температури відбувається при знаходженні оброблювального виробу у точці вимірювання температури при зупиненому переміщенні оброблювальних виробів у вакуумній камері. За результатами моніторингу температури виробів здійснюється керування напругою, яка подається на вироби. Практичне випробування розробленої системи вимірювання температури при отриманні покриттів на свердлах зі сталі Р6М5 у модернізованій установці «Булат-6» показало, що вони мають стійкість до зносу в 1,7 рази більшу, порівнюючи з такими ж свердлами, покритими нітридом титану за традиційною технологією при обробці сталі Ст45.