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## A NEW METHOD FOR MONITORING THE PRODUCT SURFACE TEMPERATURE AND ITS APPLICATION IN THE DEPOSITION OF VACUUM-ARC COATINGS

The **subject matter** of this study is the process of measuring the product surface temperature using a pyrometric method during the deposition of vacuum-arc coatings, as well as the application of the obtained results to control the coating deposition process. The **aim** of this work is to improve the stability, accuracy, and reproducibility of product surface temperature measurements for effective control of the coating deposition process. The **objectives** of the study are to develop an algorithm for monitoring the product surface temperature during coating deposition and to determine the design conditions for planetary gear trains that ensure the product positioning exactly at the temperature measurement point after each full revolution. The **methods** used in this research include analytical approaches and design methods for planetary gear trains that satisfy the specified requirements. The following **results** were obtained. Based on an analysis of existing methods for measuring the product surface temperature during coating deposition, the main disadvantages of each method were identified. The pyrometric method was determined to be the most suitable, as it allows accurate measurement of the product surface temperature once the contamination of the pyrometer's input window is resolved. An operational algorithm for the proposed pyrometric temperature measurement system for monitoring the product surface temperature was developed. The application of this algorithm during the deposition of vacuum-arc coatings at various processing stages improves coating quality. When implemented, the algorithm ensures the stability, accuracy, and reproducibility of temperature measurement results by protecting the pyrometer optics from condensation of cathode erosion products. This is achieved by switching off the plasma source, stopping the rotation of the products in the vacuum chamber, and performing the temperature measurement after a delay following the plasma source's shutdown. The temperature measurement process is carried out at each stage of vacuum-arc coating deposition, including ion cleaning and coating deposition. Temperature monitoring allows timely completion of the ion cleaning process without tempering the product material. During the coating deposition stage, it enables maintaining the product temperature at a specified level by adjusting the applied voltage. These measures help achieve high-quality coatings. Conditions were developed that make it possible to obtain a simple planetary gear train ( $\overline{AI}$ -type) in which the planets perform an integer number of revolutions per one revolution of the carrier. A sequence for the optimal kinematic and geometric synthesis of such mechanisms was also developed for their subsequent application in technological processes of vacuum-arc coating deposition. An example of the calculation of such a planetary gear train for the “Bulat-6” installation is presented. **Conclusions.** The scientific novelty of the results obtained is as follows: an algorithm for monitoring the surface temperature of workpieces during coating deposition has been developed within the proposed temperature measurement system, which incorporates a specially designed planetary gear train. This ensures precise positioning of the workpiece at the temperature measurement point and enables control of the vacuum-arc coating process based on temperature monitoring results, thereby contributing to the improvement of the quality of the resulting coatings.

**Keywords:** vacuum-arc coatings; pyrometric method; temperature measurement system; temperature measurement point; process control based on temperature monitoring results; planetary gear train.

### 1. Introduction

#### 1.1. Motivation

Temperature monitoring and control of processed products within the limits specified by the technological process is a necessary requirement for obtaining high-quality vacuum-arc coatings [1, 2]. Moreover, each ma-

terial from which a product is manufactured requires its own permissible temperature range during processing. For example, during the treatment of the products made of R6M5 steel, the temperature should be maintained within the range of 480–550 °C [3]. At lower temperatures, it is impossible to achieve high adhesion of the coating to the substrate material, whereas at higher temperatures tempering of the base material occurs.



Thus, ensuring accurate temperature control constitutes an important scientific, technical, and practical task in the field of ion-plasma coating technologies.

### 1.2. State of the art

Among all known temperature measurement methods [4–6], the main ones used in ion-plasma coating deposition technologies are the thermoelectric and pyrometric methods [1, 7]. The application of the thermoelectric method is relatively simple when the processed products remain stationary. However, when the products are in motion – which is primarily required to ensure the quality of processing – its use becomes significantly more complicated. The mechanisms developed in [7] for transmitting the electrical signal from a thermocouple placed on a product located on the planet gear of a planetary gear train and rotating both around the planet axis and around the axis of the planetary gear train itself are very complex. This complexity has resulted in their very limited practical use in industry.

A more promising method for application in coating deposition technologies is the pyrometric method of temperature measurement. This method involves directing the infrared radiation emitted from the surface of the processed products to the pyrometer sensor in order to monitor their temperature [7]. The simplicity of this method has ensured its widespread use in industry. At most enterprises where coatings were deposited on products, pyrometers of various modifications of the “Smotrych” series, manufactured by the Lviv plant “Termoprylad”, were used. The main advantage of pyrometers is that they can be employed for measuring the temperature of products that are moving or located in hard-to-reach areas, which is impossible when using thermocouples. In addition, pyrometers respond quickly to rapid temperature changes and do not distort the temperature field being measured.

However, the use of the pyrometric method in ion-plasma coating technologies (particularly in the vacuum-arc method) is complicated by the fact that the products of cathode erosion from the plasma source are deposited on the window used for transmitting the infrared radiation from the surface of the processed products. This deposition reduces the transmission capacity of the window and leads to significant errors in the temperature measurement process.

Thus, despite the availability of effective temperature measurement methods, the problem of ensuring the accuracy of pyrometric control under vacuum-arc process conditions remains insufficiently resolved.

### 1.3. Objectives and tasks

Considering the above, the aim of the study is to improve the pyrometric method for measuring the product surface temperature during vacuum-arc coating deposition processes.

The proposed approach is based on an operating principle that prevents cathode erosion products from reaching the window used to transmit infrared radiation to the pyrometer sensor. The study also includes the practical implementation of this method in the modernized “Bulat-6” installation.

To achieve this aim, within the framework of this study it is necessary to address the following tasks:

1. Analyze existing methods for measuring the product surface temperature in coating processes and to identify their main limitations in order to substantiate the applicability of the pyrometric method.

2. Examine the problem of contamination of the optical window in vacuum-arc technologies, particularly under laser initiation of pulsed vacuum arcs, and to determine possible solutions.

3. Develop an algorithm for a pyrometric temperature measurement system that ensures stability, accuracy, and reproducibility of results by protecting the optical window from cathode erosion products and performing measurements under stable conditions with precise positioning of the component.

4. Develop synthesis conditions for a simple planetary gear train that ensures an integer number of planet revolutions relative to the carrier, and to define the sequence of its kinematic and geometric design for implementation in the “Bulat-6” installation.

The article is structured as follows.

Section 2 describes the materials and research methods employed.

Section 3 provides an analysis of the current state of methods for protecting the infrared radiation output window.

Section 4 presents the operating algorithm of the temperature measurement system within the “Bulat-6” installation.

Section 5 considers the design conditions of the planetary gear train for the temperature measurement system, including its application in vacuum-arc coating technologies, the determination of conditions for ensuring an integer number of planet revolutions, and constraints on their selection.

Section 6 presents the research results and their discussion, including the analysis of existing temperature measurement methods and optical window protection approaches, the development of a pyrometric measurement algorithm, and the substantiation of planetary gear train parameters. The obtained results confirm the effectiveness of the proposed approach in improving

measurement accuracy and ensuring stable temperature control, thereby enhancing the quality of vacuum-arc coatings.

Section 7 concludes the article by summarizing the main findings and outlining prospects for further studies aimed at improving temperature control accuracy under vacuum-arc conditions.

## 2. Materials and methods of research

The object of the study is the process of product surface temperature control in vacuum-arc coating deposition technologies.

The subject of the study is the pyrometric method for measuring the product surface temperature, as well as approaches for improving measurement accuracy through protection of the pyrometer optical system from contamination and the application of a planetary positioning gear train for products.

Experimental investigations were carried out using a modernized “Bulat-6” vacuum-arc deposition installation. Temperature measurements were performed with an OPRIS CTlaser LT pyrometer, CF2 optics 75:1 series [8], which records infrared radiation emitted from the surface of the processed products. The tested samples were manufactured from tool steel, which requires strict adherence to specified temperature regimes during processing.

To ensure stable measurement conditions, a specially designed planetary gear train was employed to provide precise positioning of the product within the measurement zone.

The research methods included:

- analysis of scientific and technical literature concerning existing temperature measurement methods;
- development of an operating algorithm for the pyrometric temperature control system;
- kinematic and geometric synthesis of the planetary gear train;
- experimental validation of the proposed technical solutions under vacuum-arc coating deposition conditions.

The applied methods and the described experimental installation ensure the reproducibility of the obtained results.

## 3. Analysis of the current state of the problem of protecting the infrared radiation output window

A simple solution for protecting the optical window from contamination is based on the use of shutters that are opened during observation of the coating deposition process and closed at other times. Such a principle

has been implemented in installations of the “Bulat” series and in several other systems. To prevent contamination of the pyrometer input window, a special insert made of a NaCl single crystal was used in [9]. This insert is placed at the end of the receiving nozzle of the pyrometer and can be easily replaced or cleaned as it becomes contaminated. However, the above-mentioned simple solutions cannot be considered optimal, since they involve manual labor for cleaning or replacing the window through which the radiation passes.

The problem of protecting the radiation input window from contamination also arises in vacuum-arc technologies when laser radiation is introduced into the vacuum chamber to initiate a pulsed vacuum arc. In modern plasma sources, this problem is mainly addressed by minimizing the number of cathode erosion products (primarily vaporized material) that reach the laser beam input window. An example of the implementation of this approach is presented in [10], where the input window is protected by a shutter that opens only for a short time during the passage of the radiation. Such a solution undoubtedly reduces the amount of cathode material deposited on the input window; however, it cannot completely eliminate window contamination.

A more radical solution for protecting the laser beam input window in the pulsed plasma source with laser arc initiation was proposed by Scheibe H.-J. et al. [11, 12]. A similar approach is also used in one of the plasma source designs described in [10]. In these systems, the path of the cathode material vapor flow to the laser radiation input window is completely blocked. For this purpose, a transparent screen made of polymer material is installed in front of the window. During operation of the source, this screen moves in front of the radiation input window, continuously renewing its transparency. However, this solution significantly complicates the design of the plasma source and requires periodic replacement of the screen after a certain operating time.

To eliminate distortions in spectrometer readings, in [13] the radiation input window was completely covered with a screen, while the radiation itself was supplied to the spectrometer through a thin stainless-steel tube with a diameter of 2.6 mm and a length of 20 cm, mounted in the screen. The tube was positioned at a distance of 18 cm from the target surface at an angle of 60° to the normal. Such a design reduces contamination of the spectrometer input window, since particles from the sputtered target enter the long tube of small diameter only from a limited area of the target surface. However, this solution also cannot completely eliminate contamination of the input window.

The solutions proposed in studies [9–13] for protecting the radiation input window from contamination cannot be considered fully effective, since they signifi-

cantly complicate the design of vacuum coating deposition systems. In addition, such approaches aimed at minimizing contamination of the radiation input–output window still require its periodic cleaning or replacement.

A method for solving the problem of radiation input–output window contamination by maintaining the window temperature not lower than a certain critical temperature – dependent on the vapor flux density and at which condensation of metal vapors does not occur on any targets [14] – was analyzed in [15]. The reason for the impracticality of this approach is that maintaining the temperature of the radiation input–output window at a sufficiently high level (not lower than the melting temperature of refractory metals commonly used in vacuum-arc technologies) is extremely difficult. Moreover, the windows themselves are typically made of various types of glass. The most heat-resistant among them is quartz glass, which can withstand temperatures up to 1100 °C (and up to 1400–1500 °C for short periods) [16], which is still lower than the required level.

In many cases of vacuum-arc coating deposition involving laser initiation of a pulsed vacuum arc, a possible solution is the method for cleaning the laser radiation input window in a vacuum chamber proposed in [17]. This method involves the periodic delivery of energy by an unfocused laser beam into the condensate layer formed on the surface of the input window. The periodicity of cleaning the laser radiation input window, which determines its transmission capacity, is defined based on the condition that the probability of vacuum arc excitation must not fall below a specified level. The spot area of the unfocused cleaning laser beam  $S_{unf}$  on the input window surface facing the vacuum chamber is determined under the condition that the laser radiation power density  $q$  on the cleaned surface lies within the range  $10^4 \leq q \leq 10^5 \text{ W/cm}^2$ .

The initiation of a vacuum arc in a pulsed plasma source using this method makes it possible to remove the condensate layer from the laser radiation input window and ensures a stable probability of vacuum arc excitation of about 95% at a pulse repetition frequency of 300 Hz, regardless of the plasma source operating time. However, the application of such a method for measuring the product surface temperature by the pyrometric method in vacuum-arc coating processes is extremely complicated.

In our opinion, the most advanced method currently available for protecting the infrared radiation output window during measuring the product surface temperature in vacuum-arc coating deposition processes using the pyrometric method is the technique proposed in [18]. In this method, a shutter is used that opens with a delay after the vacuum-arc discharge has been switched off and the rotation of the substrate holder (planetary

gear train) carrying the products has stopped exactly at the temperature measurement point. This approach ensures high accuracy of the product temperature measurements. To control the coating deposition process, the developed temperature measurement system incorporates a control unit that maintains the temperature within specified limits by adjusting the voltage applied to the products. This enables stable thermal conditions to be maintained during the process and ensures high quality of the deposited coatings.

Study [18] describes the physical principles underlying the temperature measurement system. However, due to the limited scope of that work, a detailed algorithm of its operation within an ion-plasma deposition system was not presented. For the same reason, the conditions that must be satisfied during the design of the planetary gear train were not specified. These conditions ensure that after each complete revolution of the planetary gear train, the product returns to exactly the same position, thereby guaranteeing the invariability of the temperature measurement point.

#### 4. Operational algorithm of the product surface temperature measurement system integrated into the “Bulat-6” installation

The ion-plasma installation “Bulat-6” with an integrated temperature measurement system for the processed products, implemented using the proposed method [18], is shown in Fig. 1.

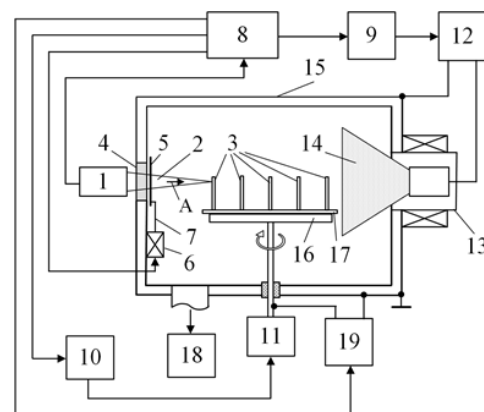


Fig. 1. Structural diagram of the system for measuring the product surface temperature during vacuum-arc coating deposition:

- 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 gear train; 17 – substrate holder; 18 – evacuation system; 19 – bias voltage source

The presented structural diagram makes it possible, based on the results of product temperature monitoring during the coating deposition process, to terminate the ion cleaning process once the specified temperature of the products is reached. It also enables regulation of their temperature within a specified range by varying the bias voltage applied to the substrate holder (planetary gear train) directly during coating deposition.

The operating algorithm of this temperature measurement system is presented in Figs. 2 and 3.

Figure 2 shows the sequence of operations during ion cleaning of the product surfaces, when heating of the products occurs simultaneously with the cleaning process. At this stage, the products are heated to the temperature at which coating deposition is subsequently carried out, which must not exceed the tempering temperature of the product material.

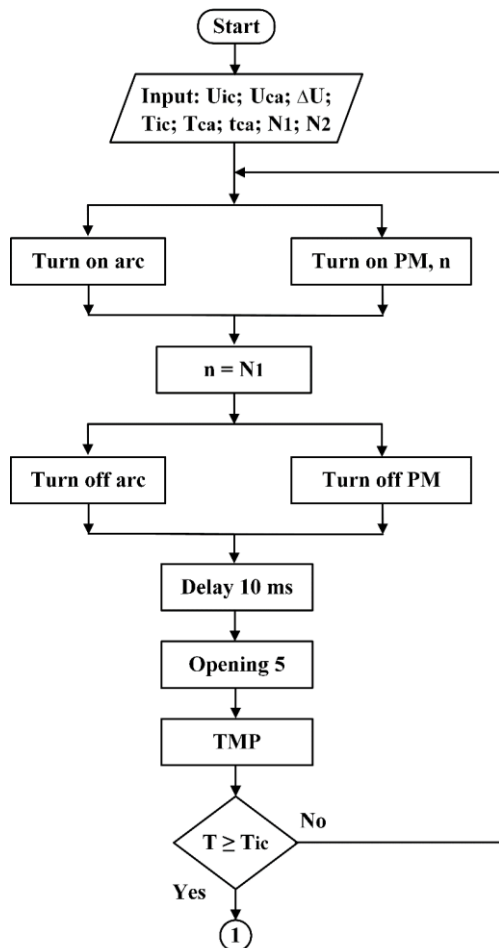


Fig. 2. Operational algorithm of the temperature measurement system in the ion cleaning mode

Figure 3 presents the algorithm of system operation in the coating deposition mode, in which the temperature required to obtain high-quality coatings is maintained by adjusting the bias voltage applied to the products.

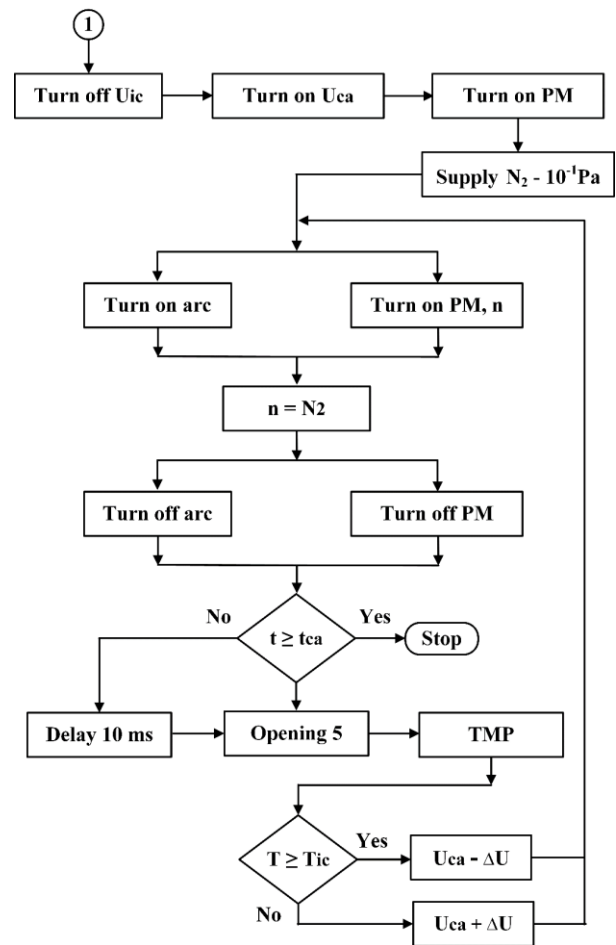


Fig. 3. Operational algorithm of the temperature measurement system in the coating deposition mode

During the development of the presented algorithms, the following assumptions were made:

- the processed products have been prepared for coating deposition and loaded into the vacuum chamber by mounting them on the planetary gear train planets (substrate holder);

- the temperature measurement point has been set on one of the processed products, selected as a reference sample for monitoring the temperature of its surface. The correct position of the temperature measurement point on the surface of the reference product (20) is shown in Fig. 4;

- a specially designed planetary gear train has been employed; whose planets return to the same position after each complete revolution;

- the installation vacuum chamber has been evacuated to a pressure of  $(1...3) \cdot 10^{-3}$  Pa;

- all installation units required for coating deposition have been prepared for operation;

- the shutter-screen has been set to the closed position.

In the algorithms shown in Figs. 2 and 3, the following symbols and abbreviations are adopted:

- **Start** – beginning of the coating deposition process;
- **Input** – input of technological process parameters into the control unit: the voltage applied to the substrate holder during ion cleaning **Uic**; the bias voltage applied to the substrate holder during coating deposition **Uca**; the voltage increment  $\Delta U$  by which **Uic** is increased or decreased during coating deposition; the maximum temperature of the products during ion cleaning **Tic**; the optimal temperature of the products during coating deposition **Tca**; the coating deposition time **tca**; the number of complete revolutions of the planetary gear train **N1** between product temperature measurements during ion cleaning; and the number of complete revolutions of the planetary gear train **N2** between product temperature measurements during coating deposition;
- **Turn on arc** – switching on the vacuum-arc discharge;
- **Turn on PM, n** – switching on the drive of the planetary gear train, where n is an integer number of complete revolutions of the planetary gear train;
- **Turn off arc** – switching off the vacuum-arc discharge;
- **Turn off PM** – switching off the drive of the planetary gear train;
- **Delay 10 ms** – delay after switching off the vacuum-arc discharge before measuring the product temperature;
- **Opening 5** – opening of the shutter-screen for temperature measurement;
- **TMP** – measurement of the product temperature;
- **Supply  $N_2 - 10^{-1} Pa$**  – supply of the reactive gas (in this case nitrogen) into the vacuum chamber up to the specified pressure ( $10^{-1} Pa$ );
- **Stop** – completion of the coating deposition process.

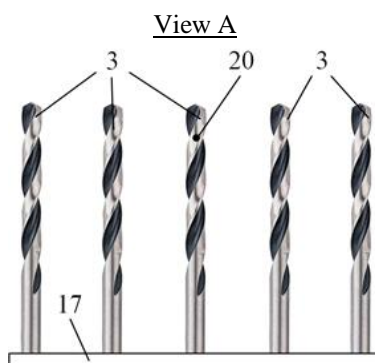


Fig. 4. Location of the pyrometer measuring spot on the processed product surface when positioned at the temperature measurement point (view A, Fig. 1): 20 – location of the pyrometer measuring spot on the processed product surface at the temperature measurement point; other designations are as in Fig. 1

## 5. Design conditions for the temperature measurement system planetary gear train

### 5.1. Application of planetary gear trains in the vacuum-arc coating deposition technologies

To increase productivity of the vacuum-arc coating deposition installations and improve the quality of the obtained coatings, planetary gear trains of various designs are used.

Modern ion-plasma installations are based on principles that were developed at the Kharkiv Institute of Physics and Technology of the Ukrainian SSR Academy of Sciences during the creation of the “Bulat”-series installations. Due to the wide range of products that could be processed in this installation, it was unfortunately not equipped with a planetary gear train. The substrate holder available in the installation was connected, through an insulated shaft, to a motor that ensured rotation of the holder with the products mounted on it at a rotational speed of 8 rpm. Therefore, at the enterprises where the installation was used, technological tooling was independently developed for specific types of products, including the use of planetary gear trains located inside the vacuum chamber.

One of the earliest installations in which a planetary gear train was serially implemented is the IET-8 system. However, its use was limited when applying coatings to relatively large products, which could not be positioned on the planets of its planetary gear train. Subsequently, with the development of modern ion-plasma installations, a significant number of systems appeared, most of which were equipped with planetary gear trains. An example of such a system is the VDU-SI vacuum-arc installation, developed by the Scientific and Engineering Center “Plasmoteg” of the Institute of Physics and Technology of the Belarus National Academy of Sciences in collaboration with the Smorgon Optical Machine-Building Plant [19].

The circular table for product placement in this installation includes 60 planetary and 180 double planetary rotation positions, all of which are easily removable. This configuration allows for mechanized loading of products into the chamber, for which the system provides the possibility of equipping the installation with specialized tooling and two sets of these positions. The circular table is driven at a rotational speed of 1.5...2.0 rpm, while the double planetary positions rotate at 30...40 rpm. The total weight of products processed in the installation can reach up to 80 kg. Unfortunately, this work provides neither an illustration of the circular table, nor an explanation of the operating principle of the applied temperature measurement system or

the method used to protect the optical system from contamination by cathode erosion products.

The original and relatively simple planetary gear train (Fig. 5) is presented in [20]. The use of this mechanism enables repeated sequential deposition of both single- and multilayer coatings on cylindrical products.

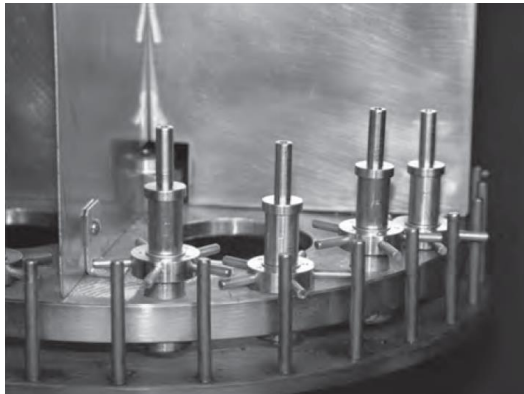


Fig. 5. One-fourth of the circular table with planetary-type substrate holders

Thus, to meet both the technological requirements of the coating process and the economic efficiency of the installations, it is necessary to design planetary gear trains specifically tailored to the type of the processed product. Moreover, when employing the proposed product surface temperature measurement system, it is essential to use a planetary gear train that ensures, with each complete revolution, the exact same orientation of the product at the initial position. The design calculation for such a planetary gear train is presented below.

## 5.2. Determination of the conditions for an integer number of planet revolutions in a planetary gear train

For the surface temperature measurement system, a modified  $\overline{AI}$ -type planetary gear train (hereinafter referred to as  $\overline{AI}$  gear train) was selected, as shown in Fig. 6. This mechanism offers advantages in terms of high efficiency and relatively compact dimensions [21].

To satisfy the condition of an integer number of planet revolutions per one full rotation of the gear train ( $N$ ), it is necessary to ensure the following ratio:

$$i_{2H}^{(3)} = \frac{\omega_2}{\omega_H} = 1 - \frac{z_3}{z_2} = N \quad (1)$$

where  $\omega$  – angular velocity,  $z$  – gear tooth number.

Since in the  $\overline{AI}$  gear train  $z_3 > z_2$ , it follows that  $N < 0$ .

The general equations for determining the gear tooth numbers in the  $\overline{AI}$  gear train have the following form [22]:

$$z_1 = \frac{kP}{i_{1H}^{(3)}}, \quad (2)$$

where  $P$  – technological parameter (natural number),  $k$  – planet number.

$$z_2 = z_1 \frac{i_{1H}^{(3)} - 2}{2}, \quad (3)$$

$$z_3 = z_1 \left( i_{1H}^{(3)} - 1 \right). \quad (4)$$

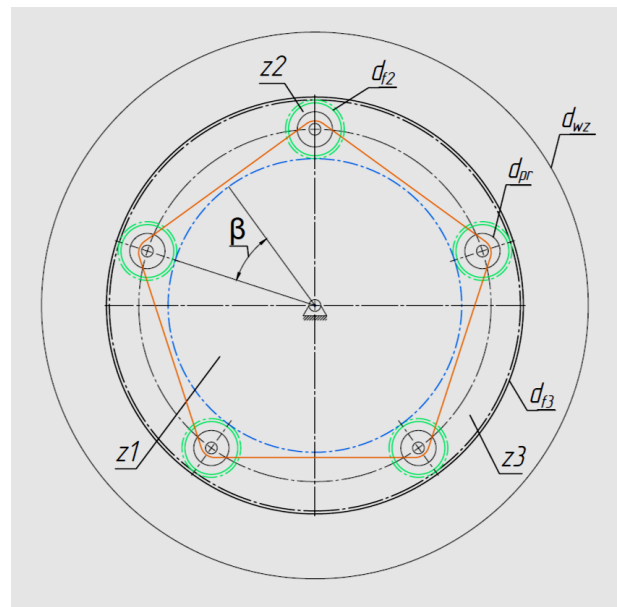


Fig. 6. Modified  $\overline{AI}$ -type planetary gear train

Substituting Eqs. (3) and (4) into Eq. (1) yields the relationship between the transmission ratio of the gear train  $i_{1H}^{(3)}$  and the transmission ratio  $i_{2H}^{(3)} = N$ :

$$i_{2H}^{(3)} = 1 - \frac{2z_1 \left( i_{1H}^{(3)} - 1 \right)}{z_1 \left( i_{1H}^{(3)} - 2 \right)},$$

from which

$$i_{1H}^{(3)} = 1 - \frac{2i_{2H}^{(3)}}{i_{2H}^{(3)} + 1} = \frac{2N}{N+1}. \quad (5)$$

Equation (5) determines the transmission ratios that satisfy Eq. (1) as a function of the parameter N (Table 1). As the absolute value of N increases,  $i_{1H}^{(3)}$  approaches 2.

Table 1

Transmission ratios of the gear train  $i_{1H}^{(3)}$  depending on the parameter N

N	-2	-3	-4	-5	-6	-7
$i_{1H}^{(3)}$	4	3	2.(6)	2.5	2.4	2.(3)
N	-8	-9	-10	-11	-12	-13
$i_{1H}^{(3)}$	2.29	2.25	2.(2)	2.2	2.(18)	2.1(6)
N	-14	-15	-16	-17	-18	-19
$i_{1H}^{(3)}$	2.15	2.14	2.1(3)	2.125	2.12	2.(1)
N	-20	-21	-22	-23	-24	-25
$i_{1H}^{(3)}$	2.105	2.1	2.095	2.091	2.087	2.083
N	-26	-27	-28	-29		
$i_{1H}^{(3)}$	2.080	2.077	2.074	2.071		

Not all transmission ratios can be realized for an arbitrary number of planet gears. To determine the range of admissible transmission ratios as a function of the number of planets, the following inequality is used [22]:

$$2 < i_{1H}^{(3)} < i_{1H \max}^{(3)}, \quad (6)$$

$$i_{1H \max}^{(3)} = \frac{2}{1 - \sin \beta}, \quad (7)$$

where  $\beta = \frac{\pi}{k}$  – half of the central angle between adjacent planets  $z_2$ , assuming their uniform distribution around the sun gear  $z_1$  (see Fig. 6).

The values of  $i_{1H \max}^{(3)}$  for selected values of k, determined using Eq. (5), are presented in Table 2.

Table 2

Values of  $i_{1H \max}^{(3)}$  for selected values of k

k	20	30	40	50
$i_{1H \max}^{(3)}$	2.371	2.233	2.170	2.134
k	54	56	60	
$i_{1H \max}^{(3)}$	2.123	2.119	2.110	

Furthermore, Eq. (5) makes it possible to express the general equations in terms of the introduced parameter N:

$$z_1 = \frac{kP(1+N)}{2N}; \quad z_2 = \frac{-kP}{2N}; \quad z_3 = \frac{kP(N-1)}{2N}. \quad (8)$$

### 5.3. Constraints imposed on the selection of the planet number

The size of the planet gear on which the product is mounted during the technological process must exceed the size of the component itself in order to ensure smooth operation of the gear train without jamming. Therefore, for example, in the case of coating drills, the diameter of the dedendum circle of the planet  $d_{f2}$  must satisfy the following condition:

$$d_{f2} > 1.2d_{pr}, \quad (9)$$

where  $d_{pr}$  – diameter of the product (drill).

From an economic standpoint, the number of planets k should be as large as possible for a given component size.

The maximum number of planets can be estimated based on the condition of their dense arrangement along the inner surface of a cylinder whose radius is equal to the radius of the working zone of the vacuum chamber (Fig. 7).

For a standard gear with the minimum number of teeth  $z_{\min} = 18$ , the addendum circle diameter is related to the dedendum circle diameter as follows:

$$\frac{d_a}{d_f} = \frac{m(z+2)}{m(z-2.5)} = \frac{18+2}{18-2.5} \approx 1.55,$$

where m – module.

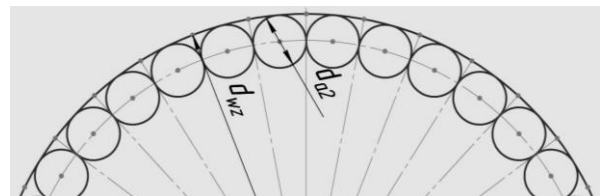


Fig. 7. Maximum number of planets of a planetary gear train

Then, taking into account condition (9), it can be obtained:

$$d_a = 1.55d_f = 1.55 \cdot 1.2d_{pr} = 1.86d_{pr}.$$

Thus,

$$k_{\max} = \frac{\pi}{\sin^{-1}\left(\frac{1.86d_{\text{pr}}}{d_{\text{wz}} - 1.86d_{\text{pr}}}\right)}, \quad (10)$$

where  $d_{\text{wz}}$  – diameter of the working zone.

To ensure the operability of the  $\overline{AI}$  gear train, the following conditions must also be satisfied:

– inter-planet interference – the possibility of arranging all planets in a common plane:

$$m(z_3 - z_2) \frac{\cos \alpha}{\cos \alpha_{\text{w}32}} \sin \frac{\pi}{k} > d_{\text{a}2}, \quad (11)$$

where  $\alpha$  – pressure angle of a standard basic rack tooth profile,  $\alpha = 20$  degrees;  $\alpha_{\text{w}32}$  – gearing  $z_2 - z_3$  pressure angle;

– condition of absence of interference in internal gearing  $z_2 - z_3$  [23];

– condition of absence of undercutting for gears with external teeth  $z_1, z_2$ :

$$z_{\min_i} \geq \frac{2h_a^*}{\sin^2 \alpha}, i = 1, 2,$$

where  $h_a^*$  – coefficient of tooth addendum,  $h_a^* = 1$ .

The overall size of the gear train is limited by the dimensions of the installation working zone:

$$d_{f3} < d_{\text{wz}}. \quad (12)$$

#### 5.4. Example of planetary gear train design for the “Bulat-6” installation

Input data: the working zone diameter  $d_{\text{wz}} = 400$  mm; the maximum diameter of the processed products  $d_{\text{pr}} = 10$  mm; economically justified minimum number of components per operating cycle: 50 units.

Calculation algorithm:

$$1. \text{ Determine } k_{\max} = \frac{\pi}{\sin^{-1}\left(\frac{1.86 \cdot 10}{400 - 1.86 \cdot 10}\right)} \approx 64.$$

2. The number of planets  $k$  is selected based on the condition  $k < k_{\max}$ :  $k = 54$ .

3. Using Eq. (7), the maximum possible transmission ratio for the selected  $k$   $i_{1H}^{(3)} = 2.123$  is deter-

mined. From condition (6), the value  $i_{1H}^{(3)} = 2.1$  is adopted. For this transmission ratio value, the parameter  $N$  is determined according to Table 1 ( $N = -21$ ).

4. Based on the general Eq. (8), the numbers of teeth are selected as follows:  $z_1 = 360$ ;  $z_2 = 18$ ;  $z_3 = 396$ . The technological parameter  $P = 14$  is calculated. The use of non-corrected gears is adopted.

5. The gear module is determined from condition (12):  $d_{f3} < d_{\text{wz}}$ ;  $mz_3 + 2m < d_{\text{wz}}$ ;

$$m_{\max} = \frac{400}{396 + 2} = 1.005 \text{ (mm)}. \text{ A standard module}$$

smaller than the calculated value is selected, namely  $m = 0.8$  mm. At this module, the gears are classified as fine-module gears.

6. A geometric design calculation of the mechanism gears is performed under the assumption that the gears are cut using a gear shaper cutter. The cutter parameters are selected in accordance with the requirements of GOST 10059–80:  $m = 0.8$  mm,  $z_0 = 32$ ,  $h_{a0}^* = 1$ ,  $c_0^* = 0.35$ ,  $x_0 = 0.35$ .

Selected geometric characteristics are presented below.

The dedendum circle diameter of the ring gear ( $z_3$ ) is:  $d_{f3} = 318.96$  mm.

The condition ( $318.96 \text{ mm} < 400 \text{ mm}$ ) confirms the feasibility of accommodating the gear train within the working zone of the “Bulat-6” installation.

The dedendum circle diameter of the planet gear ( $z_2$ ) is:  $d_{f2} = z_2 m - 2.5m = 18 \cdot 0.8 - 2.5 \cdot 0.8 = 12.22$  (mm).

Condition (9) is verified:  $12.2 > 1.2 \cdot 10$ . Condition (9) is satisfied, confirming the feasibility of mounting the processed product on the planet gear.

The addendum circle diameter of the planet is:  $d_{a2} = 16$  mm.

7. The inter-planet interference condition is verified (Fig. 8):  $(z_3 - z_2) \sin \frac{\pi}{k} > z_2 + 2$ ,

$$(396 - 18) \sin \frac{\pi}{54} > 18 + 2, 21.98 > 20. \text{ The inter-planet}$$

interference condition is satisfied.

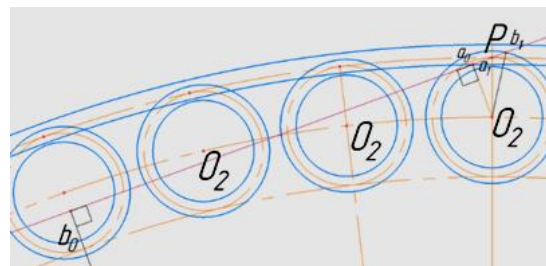


Fig. 8. Inter-planet interference condition verification

8. The following conditions for the absence of interference [22] are verified:

- undercutting of the pinion teeth during shaping with the cutter;
- removal of ring gear tooth material by the cutter's fillet curve;
- interference between the ring gear tooth tip edges and the fillet surface of the pinion teeth;
- interference between the pinion tooth tip edges and the fillet surface of the ring gear teeth;
- interference between the teeth of the pinion and the ring gear.

All conditions are satisfied; no interference is observed.

At this stage, the kinematic and geometric synthesis of the  $\overline{AI}$  gear train is considered complete.

According to [22], to ensure the strength of the gear teeth, the numbers of teeth of the central gears and the planets should not have common factors; alternatively, the sum of the greatest common factors should be minimized as much as possible. In addition, to achieve favorable vibration characteristics of the planetary gear train, the numbers of teeth of the central gears should not be multiples of the number of planets.

Unfortunately, Eq. (1) contradicts these requirements. However, since the developed gear train is not intended for power transmission and operates at relatively low angular velocities (the carrier speed is 8 rpm and the operating duration of the installation is 25 min), the use of such tooth numbers is considered acceptable.

## 6. Results and discussion

The obtained results are structured in accordance with the research objectives.

Within the framework of the first research objective, an analysis of existing methods for measuring the product surface temperature during coating deposition processes was carried out. It was established that thermoelectric methods, despite their simplicity of implementation, are poorly suited for conditions involving the rotation of products in a vacuum chamber. In contrast, the pyrometric method provides non-contact measurement and high response speed; however, its application is limited by the problem of contamination of the optical system.

For the second research objective, existing approaches to protecting the infrared radiation output window from contamination by cathode erosion products were analyzed. It was established that the currently applied solutions, including shutters in vacuum systems, replaceable optical inserts [9], moving protective screens [10–12], and elongated radiation transmission channels [13], allow only partial reduction of material deposition on optical elements and do not completely

eliminate this phenomenon. Moreover, these approaches either significantly complicate the design of the vacuum system or require periodic maintenance. It was also shown that alternative methods, such as preventing condensation by heating the window [15] or laser cleaning of its surface [17], are difficult to implement under conditions of pyrometric temperature control. Therefore, the analysis results indicate the absence of a universal technical solution, which necessitates the development of an effective method for protecting the pyrometer optical system without complicating the installation design or disrupting the technological process.

For the third research objective, a method and operating algorithm for the pyrometric temperature measurement system were developed to eliminate the influence of cathode erosion products on the optical system. Temperature measurements are performed at each stage of the vacuum-arc coating process, including ion cleaning and coating deposition. Continuous temperature monitoring enables timely completion of the ion cleaning process without tempering the product material and allows the product temperature to be maintained within the specified range during coating deposition by adjusting the applied voltage. These measures contribute to the production of high-quality coatings.

In addition, measurement reproducibility is ensured through precise positioning of the product within the measurement zone. For this purpose, a planetary gear train is employed to guarantee that temperature is measured at the same point on the product surface during each measurement cycle.

For the fourth research objective, synthesis conditions were developed for a simple  $\overline{AI}$ -type planetary gear train in which the planets perform an integer number of revolutions per one revolution of the carrier. A procedure for the optimal kinematic and geometric synthesis of such a mechanism was proposed for its subsequent application in vacuum-arc coating technologies, enabling stable positioning of the products during processing. The proposed design solutions were practically implemented in the modernized Bulat-6 installation, and an example of the planetary gear train calculation for this installation is provided.

The high metrological performance of the developed system is achieved by ensuring that temperature measurements are consistently conducted under identical conditions, namely when the product is stationary (with rotation stopped) at a predefined measurement point established during system calibration. The precise product positioning at the measurement point after each rotation of the substrate holder is ensured by the operating mode of the stepping motor and the use of a specially designed planetary gear train of the substrate holder.

The obtained results demonstrate that the proposed approach improves the quality of vacuum-arc coatings

by enabling reliable temperature monitoring and technological process control based on the measured data.

The scientific novelty of the study lies in the development of a fundamentally new pyrometric method for measuring the product surface temperature during vacuum-arc coating deposition, which ensures high measurement accuracy and reproducibility. The principal innovations of the proposed method include temporary interruption of the vacuum arc during temperature measurement, delayed opening of the shutter protecting the pyrometer optical system from contamination by cathode erosion products, and the use of a planetary gear train that ensures temperature measurement at the same point on the product surface. This combination effectively eliminates the influence of contamination and provides stable and accurate measurement results, which is essential for improving the quality of vacuum-arc coatings.

## 7. Conclusions

1. An analysis of existing temperature measurement methods used in coating deposition technologies was carried out, and the applicability of the pyrometric method for vacuum-arc processes was substantiated.

2. It was established that the primary factor reducing the accuracy of pyrometric measurements is contamination of the optical system input window by cathode erosion products, which necessitates the development of dedicated protection methods.

3. An operating algorithm for the pyrometric temperature measurement system was developed to ensure stability, accuracy, and reproducibility of measurement results by eliminating the influence of cathode erosion products and conducting measurements under controlled conditions.

4. Synthesis conditions for a planetary gear train were developed to ensure an integer revolution ratio of the planets relative to the carrier and to enable precise positioning of the product within the temperature measurement zone.

Prospects for further research involve extending the proposed method to other PVD coating deposition processes, including thermal, magnetron, and related modified technologies.

**Contributions of authors:** conceptual methodology, problem formulation – **Iurii Sysoiev**, the planetary gear train synthesis – **Olha Kladova**, modeling and calculation of the planetary gear train – **Mykyta Kovalov**, implementation, visualization, and documentation – **Yevhen Fesenko**, development and implementation of the measurement algorithm – **Yurii Shyrokyi**.

## Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship, or otherwise, that could affect the research and its results presented in this paper.

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## Data availability

The manuscript contains no associated data.

## Use of artificial intelligence

The authors confirm that they did not use artificial intelligence methods while creating the presented work.

All authors have read and agreed to the published version of this manuscript.

## References

1. Andreev, A. A., Sablev, L. P., & Grigorev, S. N. *Vakumno-dugovye pokrytiya* [Vacuum-arc coatings]. Kharkiv: NNTs KhF-TI, 2010. 318 p.
2. Muhammed, M., Javidani, M., Sadrabadi, T. E., Heidari, M., Levasseur, T., & Jahazi, M. A Comprehensive Review of Cathodic Arc Evaporation Physical Vapour Deposition (CAE-PVD) Coatings for Enhanced Tribological Performance. *Coatings*, 2024, vol. 14, iss. 3, article no. 246. DOI: 10.3390/coatings14030246
3. Kanyuka, V. I., Terekhov, V. N., & Moroz, A. N. *Spravochnik po instrumentalnym stalyam* [Handbook of tool steels]. Ed. by Yu. F. Ternovyi. Kharkiv: Metalika, 2008. 224 p.
4. Gerashchenko, O. A., Gordov, A. N., Lakh, V. I. et al. *Temperaturnye izmereniya: spravochnik* [Temperature measurements: handbook]. Ed. by O. A. Gerashchenko. Kyiv: Naukova dumka, 1984. 494 p.
5. Childs, P. R. N. *Practical Temperature Measurement*. Oxford, Butterworth-Heinemann, 2001. 372 p.
6. Michalski, L., Eckersdorf, K., Kucharski, J., & McGhee, J. *Temperature Measurement*. Chichester: John Wiley & Sons, 2001. 518 p. DOI: 10.1002/0470846135
7. Vnukov, Yu. N., Markov, A. A., Lavrova, L. V., & Berdyshev, N. Yu. *Nanesenie iznosostoykikh pokrytiy na bystrorezhushchiy instrument* [Deposition of wear-resistant coatings on high-speed cutting tools]. Kyiv: Tekhnika, 1992. 143 p.
8. Sysoiev, Iu., Shyrokyi, Yu., & Fesenko, K. Modern Methods of Vacuum Arc Ignition in Technological Plasma Sources. *Problems of Atomic Science and Technology (PAST)*, 2026, № 1(161), pp. 184-190. DOI: 10.46813/2026-161-184

9. Andreev, A. A., Grigorev, S. N., Stolbovoy, V.A. et al. Pyrometr dlya vakuumno-dugovykh ustanovok [Pyrometer for vacuum-arc installations]. *Eastern-European Journal of Enterprise Technologies*, 2010, no. 5/1 (47), pp. 21–25.
10. Volkov, V. V., Miroshkin, S. I., Shalimov, S. V., & Savelyev, A. A. *Sposob polucheniya pokrytiy v vakuume, ustroystvo dlya polucheniya pokrytiy v vakuume, sposob izgotovleniya ustroystva dlya polucheniya pokrytiy v vakuume* [Method for obtaining coatings in vacuum, device for obtaining coatings in vacuum, method for manufacturing the device]. RF Patent no. 2176681, IPC C23C14/00, appl. 22.11.1989, publ. 10.12.2001.
11. Scheibe, H.-J. & Dreschner, D. Preparation of diamond-like films by laser-controlled arc deposition (laser-arc). In: *Proceedings of the Joint 4th International Symposium TATF'94 and the 11th Conference HVITF'94*, Dresden, March 7–11, 1994, pp. 139–142.
12. Scheibe, H.-J., Siemroth, P., Schöneich, B., & Mucha, A. Diamond-like carbon film preparation by laser arc. *Surface and Coatings Technology*, 1992, vol. 52, pp. 129–133. DOI: 10.1016/0257-8972(92)90037-B
13. Tumarkin, A. V., Khodachenko, G.V., Kaziev, A.V. et al. Magnetronnyi razryad s rasplavlyennym katodom [Magnetron discharge with a molten cathode]. *Uspekhi prikladnoi fiziki*, 2013, vol. 1, no. 3, pp. 276–282.
14. Rideal, E. K. *Concepts in Catalysis*. Academic Press, 1968. 194 p.
15. Sysoiev, Iu., Shyrokyi, Yu., & Sysoiev, A. Zapaluvannia vakuumno-duhovoho rozriadu v dzherelakh plazmy netradytsiinymy metodamy [Ignition of a vacuum arc discharge in plasma sources by non-traditional methods]. *Aerospace Technic and Technology*, 2022, no. 4(180), pp. 36–45. DOI: 10.32620/akt.2022.4.04
16. Considine, G. D. (ed.), Gallagher, G., & Kulik, P. H. (assoc. eds.) *Van Nostrand's Encyclopedia of Chemistry*. 5th ed. Hoboken, NJ: Wiley-Interscience, 2005. 1831 p. DOI: 10.1333/s00897050918a
17. Sysoiev, Yu. O., Shyrokyi, Yu. V., & Fesenko, K. V. Pulsed Vacuum-Arc Plasma Source with Laser Arc Excitation. *Problems of Atomic Science and Technology (PAST)*, 2024, № 1(149), pp. 110-115. DOI: 10.46813/2024-149-110
18. Sysoiev, Iu., Shyrokyi, Yu., & Fesenko, K. System for Measurement the Product Surface Temperature for Vacuum-Arc Coatings. *Problems of Atomic Science and Technology (PAST)*, 2025, № 2(156), pp. 171-176. DOI: 10.46813/2025-156-171
19. Denizhenko, A. G., Tochitskiy, E. I., Selifanov, O. V., Mochailo, E. V., & Sheleg, V. V. Vakumnaya elektrodugovaya ustanovka so statsionarnymi i impulsnymi istochnikami plazmy [Vacuum-arc installation with stationary and pulsed plasma sources]. *Vestnik Polotskogo gosudarstvennogo universiteta. Seriya B*, 2005, no. 6, pp. 103–108.
20. Demchyshyn, A. V., Mychenko, V. A., Avtonomov, G. A., & Tokarev, O. A. Modifitsirovannaya vakuumno-dugovaya ustanovka "Bulat-3T" [Modified vacuum-arc installation "Bulat-3T"]. *Sovremennaya elektrometallurgiya*, 2009, no. 3 (86), pp. 40–42.
21. Kinytskyi, Ya. T. *Teoriia mekhanizmiv i mashyn* [Theory of mechanisms and machines]. Kyiv: Naukova dumka, 2002. 660 p.
22. Usik, V. V. & Menshikov, V. O. *Kurs teorii mekhanizmiv i mashyn* [Course of theory of mechanisms and machines]. Kharkiv: Natsionalnyi aerokosmichnyi universytet "KhAI", 2019. 320 p.
23. Tkachenko, V. A. *Planetarni mekhanizmy (optymalne proektuvannia)* [Planetary mechanisms (optimal design)]. Kharkiv: Natsionalnyi aerokosmichnyi universytet "KhAI", 2003. 446 p.

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## НОВИЙ МЕТОД МОНІТОРИНГУ ТЕМПЕРАТУРИ ПОВЕРХНІ ВИРОБІВ І ЙОГО ВИКОРИСТАННЯ ПРИ ОТРИМАННІ ВАКУУМНО-ДУГОВИХ ПОКРИТТІВ

Ю. О. Сисоєв, О. Ю. Кладова, М. П. Ковальов, Є. І. Фесенко, Ю. В. Широкий

**Предметом** вивчення в статті є процеси вимірювання температури оброблюваних виробів пірометричним методом при нанесенні вакуумно-дугових покриттів і застосування отриманих результатів для керування процесом отримання покриттів. **Метою** роботи є підвищення стабільності, точності і відтворюваності результатів вимірювання температури виробів для керування процесом отримання покриттів. **Завдання:** розробити алгоритм моніторингу температури поверхні виробів при нанесенні покриттів і знайти умови проектування планетарних механізмів, які забезпечують після кожного повного оберту позиціонування виробу точно у точці вимірювання температури. Використовуваними **методами** є аналітичні, та методи проектування планетарних механізмів із забезпеченням заданих вимог. Отримані наступні **результати**. 1. На основі результатів аналізу відомих методів вимірювання температури поверхні оброблюваних виробів в процесі

отримання покриттів виявлено основні недоліки кожного методу і визначено пірометричний метод як такий, що дозволяє при вирішенні проблеми запилення вхідного вікна оптичної системи пірометра вимірювати температуру поверхні виробів з високою точністю. 2. Розроблено алгоритм роботи запропонованої системи вимірювання температури поверхні оброблюваних виробів пірометричним методом, застосування якого для моніторингу температури при отриманні вакуумно-дугових покриттів на різних етапах оброблення підвищує їх якість. При реалізації алгоритм забезпечує стабільність, точність і відтворюваність результатів вимірювання температури виробів захистом оптики пірометра від конденсації на ньому продуктів ерозії катода шляхом вимикання джерела плазми, припиненням обертання виробів у вакуумній камері і здійсненням вимірювання температури з затримкою після вимикання джерела плазми. Процес вимірювання температури здійснюється на кожній стадії отримання вакуумно-дугових покриттів – іонного очищення і нанесення покриттів. Моніторинг температури виробів дозволяє своєчасно завершити процес іонного очищення без відпуску матеріалу виробів, а в процесі нанесення покриттів піддержувати температуру виробів на заданому рівні зміною напруги на них. Таки заходи сприяють отриманню покриттів високої якості. 3. Розроблено умови, що дозволяють отримати планетарний простий механізм (типу  $\overline{AT}$ ), в якому сателіти роблять цілу кількість обертів на один оберт водиля. 4. Розроблено послідовність оптимального кінематичного і геометричного синтезу таких механізмів для подальшого використання у технологічних процесах отримання вакуумно-дугових покриттів. Наведено приклад розрахунку такого планетарного механізму для установки «Булат-6». **Висновки.** Наукова новизна отриманих результатів полягає в наступному: розроблено алгоритм моніторингу температури поверхні виробів при нанесенні покриттів запропонованою системою вимірювання температури, в якій використано спеціально спроектований планетарний механізм. Це забезпечує точне позиціонування виробу в точці вимірювання температури і керування процесом отримання вакуумно-дугових покриттів за результатами температурного моніторингу, що, у свою чергу, сприяє підвищенню якості отриманих покриттів.

**Ключові слова:** вакуумно-дугові покриття, пірометричний метод, система вимірювання температури, точка вимірювання температури, керування процесом по результатам моніторингу температури, планетарний механізм.

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