Methodology for the Experimental Calculation the Coefficients of the Functional Dependencies Electrical Circuits Plasma Substitution

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Abstract. The article discusses the electrical equivalent circuit for installing a plasma generator in order to highlight the functional dependencies of the steady state of the control system. Experimentally established effect coating mechanism using tungsten carbides and rare earth impurities to the process of increasing resistance parts, which depends specifically introduced into the plasma generation system of controlled variables of internal resistances. This allows the use of a functionally stable control system for a non-stationary plasma medium. Experimental studies have confirmed that plasma formation occurs with the necessary parameters due to voltage stabilization at the target cathode and anode. Also, in order to stabilize the process, it is necessary to correct the current of the ionized flow, and equalize the energy potential of charged particles of the ion-plasma medium. To maintain the specified parameters within specified limits, it is necessary to introduce the corresponding resistance variables into the plasma generation system. Resistance variables are combined into a block of ballast resistors, which ensures the stability of the plasma formation and affects the value of current or voltage. These derived variable coefficients help maintain the functional stability of the specified parameters within the specified limits. This suggests that it is possible to control the flow of ionized particles by controlling their internal resistance. Due to this, the deposition of the tungsten carbide mixture on the workpiece is controlled. Coating using tungsten carbides and rare earth impurities is one of the most common in the production of tools that require high hardness, corrosion resistance and wear resistance.

Keywords: Electrical circuit · Coefficients of functional stability · Functional stability · Current stabilization · Internal resistance

1 Introduction

Many factors influence the working conditions and aircraft carrying capacity. A special factor is not only the usefulness of control systems for such devices, but also the satisfactory condition of the components that make up the main structure.

Material, shape, internal structure effect the efficiency of the system as a whole. Therefore, it is necessary that the physical and chemical characteristics of the elements

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of the control system ensure reliability and correspond to the quality of transition processes. This study is relevant due to the given growing of demand for increased wear resistance of parts.

The method which able to obtain uniform coatings on relatively complex surfaces without moving small products is the vacuum-condensation coating method. It involves the use of a particulate flux of a substance at the level of atoms, molecules, ions and the interaction of this flux with the surface of a solid. The consequence of this interaction is condensation - the deposition of a substance on a coating surface or saturation of a surface layer with a substance. All processes take place under vacuum. This choice caused by plasma methods advantages as environmentally friendly impact, safe and less energy-intensive action [1].

The aim of the work is to design a modern control system to form a stable directed plasma flow of the parts of argon, an increase in the corrosion-resistant part is processed.

To achieve this goal, it is necessary to choose the optimal option for applying an ionized coating, it is necessary to analyze the parameters and characteristics of the sputtering of particles, consider the modes of obtaining a coating by ion-plasma technology, conduct an experiment with the operation of the internal resistance control system, and ensure current stability in the gas environment of the plasma generator chamber.

1.1 Discharge Mechanism, Parameters and Characteristics of Magnetron Sputtering Systems

Anomalous scattering in magnetron sputtering systems occur at the intersection of electric and magnetic fields. Electrons moving toward the target by ion bombardment are captured by a magnetic field and perform complex cycloid motion along closed paths near the target surface. As a result of numerous collisions of electrons with the working atoms of the gas, the degree of plasma ionization increases sharply. At the same time, the ion current density increases by about 100 times in comparison with diode sputtering systems without a magnetic field. This leads to an increase in the spraying rate of the target material (50…100 times).

Since magnetic induction increases the path of electrons, the number of collisions with atoms of the working gas increases simultaneously. That is why the application of a magnetic field is equivalent to an increase in gas pressure.

The presence of inhomogeneous crossed electric and magnetic fields in magnetron sputtering systems does not allow us to fully describe all discharge parameters using existing theories. As a result of studying magnetron sputtering systems in a characteristic region for magnetic inductions of 0.03…0.1 T and pressures of 0.1…10 Pa, a model of magnetron sputtering has been developed. The model based on analytical expressions for current-voltage characteristics describes, to a first approximation, the processes occurring in magnetron sputtering systems. A method has also been developed for calculating magnetron sputtering systems, which relates the sputtering rate to the process parameters: magnetic induction, working gas pressure, voltage on the target, ion current density, an experimental method for calculating magnetron sputtering systems has been developed. This model is suitable for the approximate calculation of magnetron sputtering systems in the initial period of a pronounced erosion zone [2].

The main advantages of the magnetron sputtering system are:

(1) universality of the process, allows to obtain a layer of metals, alloys, semiconductors and dielectrics;
(2) high level of deposition (up to several microns/min.) And the possibility of its regulation over a wide range;
(3) preservation of stoichiometry when spraying complex substances;
(4) high purity of layers;
(5) high adhesion of the substrate layers;
(6) the possibility of changing the structure and properties of the layers due to the displacement potential on the substrate, the pressure and composition of the gaseous medium, the synchronous sputtering of several targets and other methods;
(7) low porosity of the layers even with a small thickness;
(8) radiation and thermal effects on the treated structure are lower than in conventional diode atomization systems;
(9) the possibility of carrying out the process in a reactive medium, which allows to obtain layers of carbides, nitrides, oxides and other compounds;
(10) the ability of a number of materials at high current density to the target to spray independently;
(11) high energy efficiency of the process compared to diode and triode spray systems;
(12) the ability to automate the process;
(13) process inversion, which allows it to be used for deposition and etching of a wide class of materials.

2 The Operating Mode of the Vacuum System of the Plasma Generator

In general, the vacuum system has the form shown in Fig. 1 and consists of a hollow tank 1 from which air is pumped out, pressure gauges 2, valve 3, pipeline 4 and pump 5.

Before the pump starts, the pressure in the entire vacuum system is the same and the gas is stationary. With the beginning of the pump, the gas begins to move from the hollow tank 1 by pipeline 4 to the pump 5. At the same time, the amount of gas in the vacuum system is continuously decreasing, and since the volume and temperature of the gas remain almost unchanged, a decrease in pressure in the vacuum system occurs. The pH pressure at the inlet to the pump becomes lower than the pressure p at the outlet of the evacuated hollow tank 1. Thus, a p-pH pressure difference is created, which is due to the presence in the system of a pipeline, a tap and other elements that resist gas flow. The difference in p-pH is called the pressure difference, carries out the movement.

In connection with the difference in the rate of pressure reduction in the hollow tank 1 and at the pump inlet (the need to consider when synthesizing control and selecting elements of the vacuum system), the concepts of gas pumping speed from the hollow tank and the speed of the pump are distinguished [3].

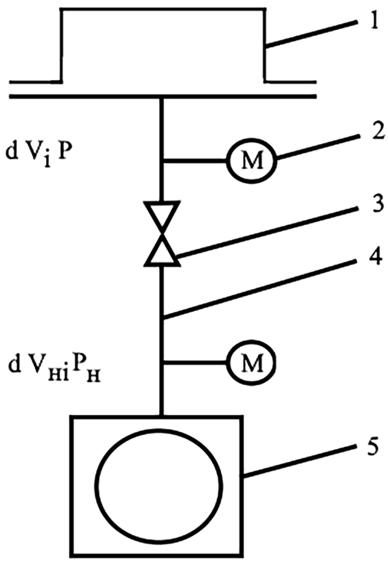

Fig. 1. General view of the vacuum system

3 Method of Ensuring Functional Stability

The empirical physical law (1) of the relationship of voltage, current and resistance (Ohm's law) makes it possible to identify the functional dependencies of the control object

$$I = \frac{\varepsilon}{R + r} \tag{1}$$

where ε – the electromotive force of the voltage source;
I – the value of the current of the electrical circuit;
R – the resistance of all external elements of the electrical circuit;
r – internal resistance of the power source.

Since a voltage source is used to power the technological installation of the plasma generator, we have:

$$R >> r \tag{2}$$

According to (2) write formula (1) so:

$$I = \frac{\varepsilon}{R} \tag{3}$$

The voltage across the entire power supply remains unchanged when internal electrical processes are unstable:

$$U = U_{con} + U_{discon} + U_{\sim} = const \quad (4)$$

where U – power source voltage;
U_{con} – value of voltage drop on analog elements;
U_{discon} – value of voltage drop on discrete elements;
$U_{\sim}$ – AC voltage of the non-stationary area of the system.

The stability of the technological process of applying a chrome coating in the framework of the use of magnetron sputtering systems using section-targeted cathodes is possible with the retention of electrical processes in a given region of the current-voltage characteristics of the gas discharge.

Ensuring the stable state of the sputtering process is also directly related to the stabilization of the current, which acts as a driving and regulating force for the directional motion of electric charges in the plasma environment.

This means that in the case of alternating uncontrolled voltage on the one hand, and due to the task of stabilizing the gas discharge gas on the other, the only control parameter of the system is resistance:

$$U = f(U_{\sim}) = f(R_{add)} \quad (5)$$

This means that if there is uncontrolled pressure from one side, then in order to create functional stability and increase the corrosion resistance of the workpiece, it is necessary to create a functional stable control system with controlled internal resistance [4], which can stabilize the voltage on the target cathode and anode, stabilize the current of the ionized stream and normalize the energy potential of charged particles Fig. 2.

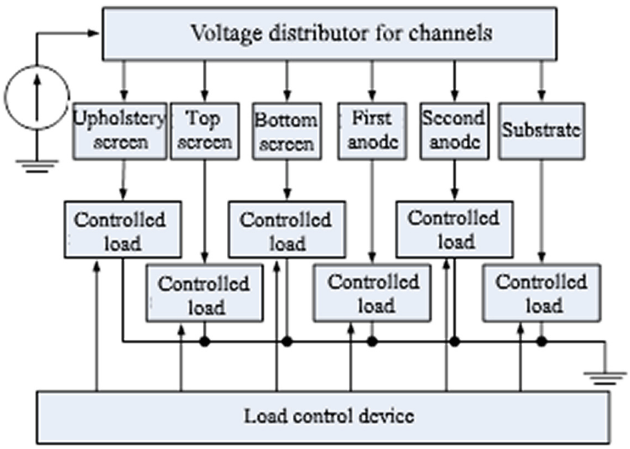

Fig. 2. Generalized structure for controlling spraying modes

The size of the controlled load is selected taking into account the voltage and currents that are realized during the operation of the plasma generator, taking into account the current-voltage characteristics of the main discharge [5]. This indicates that the flow of ionized particles can be controlled by their internal resistance.

3.1 Manual Resistance Control

In the first phase of the plasma generator control system study, alternating resistance relays were used to manually adjust the settings of work zone [6]. This means that to change the mode of application of the coating, it was necessary to stop the generator each time. It took a lot of time to change the characteristics of the system, not to mention the energy costs of the plasma-forming gas.

The implementation of a functionally stable system for controlling a plasma generator will make it possible to level out time and energy expenditures by getting the main coefficients of the system and their functional dependences [7] with the physical parameters of the plasma, namely, current, resistance, and voltage.

To solve this problem, initial experimental studies of the installation of a plasma generator were carried out and the current-voltage characteristics of the anode and cathode were obtained.

The current-voltage characteristics of the cathode and the anode under these operating conditions are shown in Figs. 3 and 4 respectively.

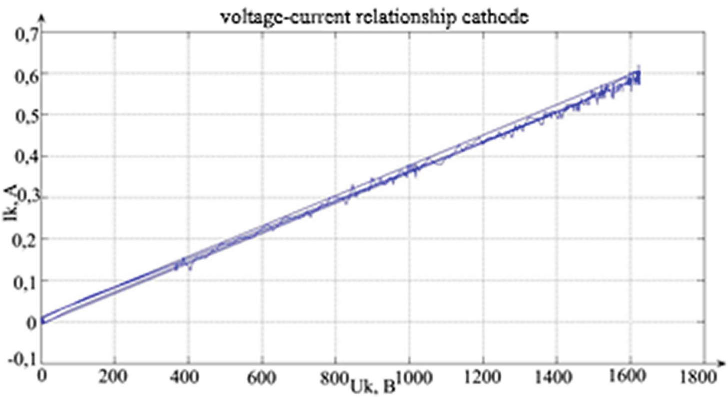

Fig. 3. Current-voltage characteristics of the cathode

These volt-current characteristics of the channels of the control system of the plasma generator make it possible to detect the jump transitions from one value to another, which does not allow to smoothly control the application of the coating to the workpiece. Such an unmanaged process gives an uneven thickness of the protective layer, which leads to a shift of the center of pressure of the workpiece, the loss of a high-quality index of surface wear resistance and, as a consequence, a rapid failure.

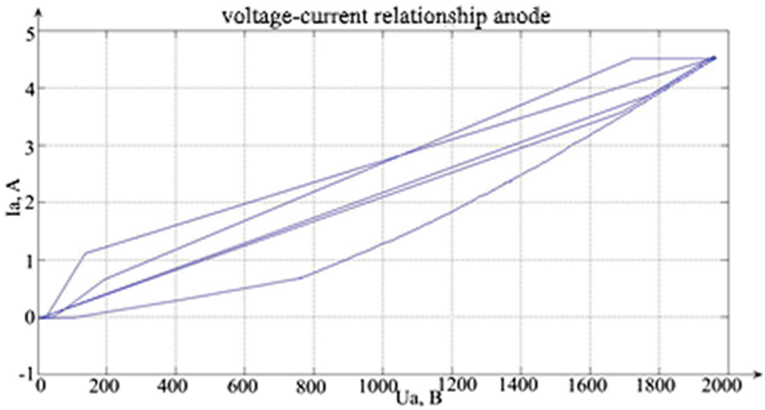

Fig. 4. Voltage-current relationship anode

3.2 Calculation of Functional Resistance Coefficient

It is quite difficult to describe plasma as a typical unit of a control system, since plasma does not have geometric parameters and, in this case, certain, regular laws of behavior.

In this regard, it is proposed to describe the sources of plasma, namely the cathode and anode. We represent the cathode and anode in the form of variable nonlinear resistors. Functionally, this can be represented as follows Fig. 5.

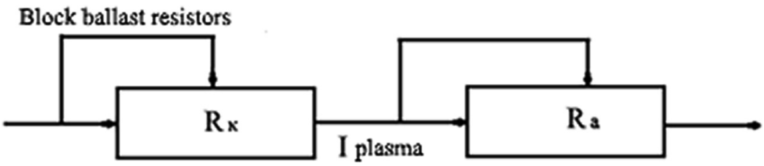

Fig. 5. Functional connection of the cathode and the anode

The need to develop new methods for ensuring functional stability is associated with the promise of using a plasma generator to solve the problem of applying protective coatings and the ability to control its composition [8]. In this case, not only the location of the components of the generator chamber is important, but also the provision of optimal characteristics of the plasma medium.

To achieve this research goal, a simplified electrical circuit of the installation under study was obtained (Fig. 6).

In the figure, respectively, R1 and R2 are included in the target cathode circles, R3 and R4 are included in the circle of the upper and lower end screens, and R5 is included in the side circle, the resistance of which changes from 1 Step to 4095 Ohms, depending on the task and voltage control on switch gear inlet.

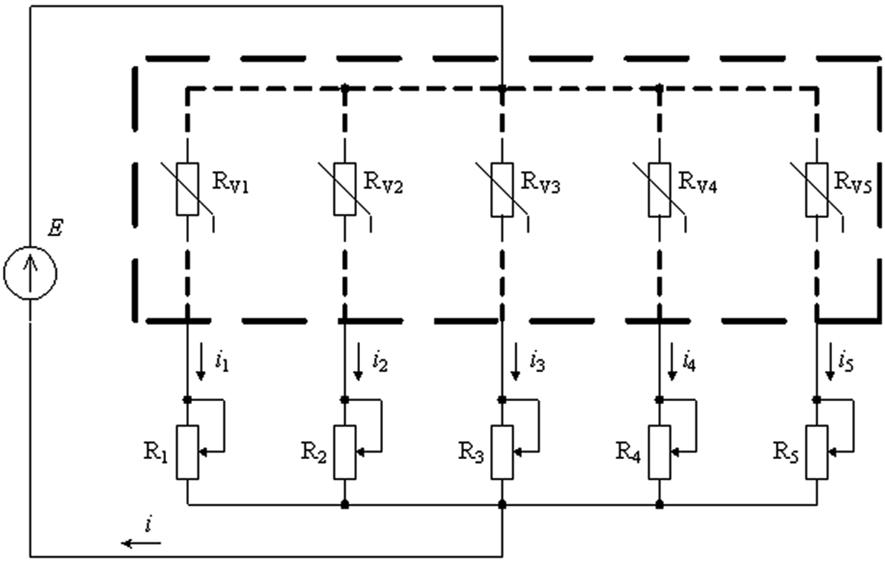

Fig. 6. Schematic diagram of the replacement of the plasma generator model

In this case, a set of resistances is formed in such a way that the nominal resistance is selected in accordance with the polynomial:

$$R_{\Sigma} = a_0 2^0 (1\Omega) + a_1 2^1 (1\Omega) + \ldots + a_k 2^k (1\Omega) = \left(a_0 + 2a_1 + \ldots + a_k 2^k\right)\Omega, \quad (6)$$

where $a_i = [0; 1]$, i.e. a_i takes 0 or 1.

Based on the equivalent scheme using the second Kirchhoff law, a system of equations was obtained:

$$\begin{cases} I_1 R_{V1} + I_1 R_1 = E; \\ I_2 R_{V2} + I_2 R_2 = E; \\ I_3 R_{V3} + I_3 R_3 = E; \\ I_4 R_{V4} + I_4 R_4 = E; \\ I_5 R_{V5} + I_5 R_5 = E. \end{cases} \quad (7)$$

In accordance with the conditions of providing a functionally stable mode $E = const$, $I_1 = const$, $I_2 = const$, $I_3 = const$, $I_4 = const$, $I_5 = const$, where $I_1 = \frac{E}{R_{V1} + R_1}, \ldots, I_5 = \frac{E}{R_{V5} + R_5}$.

The plasma formation process is unstable due to this RV1…RV5 has a variable resistance. To ensure direct current, it is necessary that R1…R5 varied so as to satisfy the conditions:

$$R_{V1} + R_1 = const.$$

If the resistances R1…R5 are independent variables, and the resistances RV1…RV5 are dependent, then we obtain the following equation:

$$\begin{gathered} R_{V1} = f(R_1, R_2, R_3, R_4, R_5); \\ R_{V2} = f(R_1, R_2, R_3, R_4, R_5); \\ R_{V3} = f(R_1, R_2, R_3, R_4, R_5); \\ R_{V4} = f(R_1, R_2, R_3, R_4, R_5); \\ R_{V5} = f(R_1, R_2, R_3, R_4, R_5); \end{gathered}$$

After the differentiation get:

$$\begin{cases} dR_{V1} = \frac{\partial R_{V1}}{\partial R_1} dR_1 + \frac{\partial R_{V1}}{\partial R_2} dR_2 + \frac{\partial R_{V1}}{\partial R_3} dR_3 + \frac{\partial R_{V1}}{\partial R_4} dR_4 + \frac{\partial R_{V1}}{\partial R_5} dR_5; \\ dR_{V2} = \frac{\partial R_{V2}}{\partial R_1} dR_1 + \frac{\partial R_{V2}}{\partial R_2} dR_2 + \frac{\partial R_{V2}}{\partial R_3} dR_3 + \frac{\partial R_{V2}}{\partial R_4} dR_4 + \frac{\partial R_{V2}}{\partial R_5} dR_5; \\ dR_{V3} = \frac{\partial R_{V3}}{\partial R_1} dR_1 + \frac{\partial R_{V3}}{\partial R_2} dR_2 + \frac{\partial R_{V3}}{\partial R_3} dR_3 + \frac{\partial R_{V3}}{\partial R_4} dR_4 + \frac{\partial R_{V3}}{\partial R_5} dR_5; \\ dR_{V4} = \frac{\partial R_{V4}}{\partial R_1} dR_1 + \frac{\partial R_{V4}}{\partial R_2} dR_2 + \frac{\partial R_{V4}}{\partial R_3} dR_3 + \frac{\partial R_{V4}}{\partial R_4} dR_4 + \frac{\partial R_{V4}}{\partial R_5} dR_5; \\ dR_{V5} = \frac{\partial R_{V5}}{\partial R_1} dR_1 + \frac{\partial R_{V5}}{\partial R_2} dR_2 + \frac{\partial R_{V5}}{\partial R_3} dR_3 + \frac{\partial R_{V5}}{\partial R_4} dR_4 + \frac{\partial R_{V5}}{\partial R_5} dR_5; \end{cases} \tag{8}$$

If replace the differentials with small increments $A = (\partial R_{V1})/(\partial R_1)$ obtain the variables:

$$\begin{cases} \Delta R_{V1} = A_{11}\Delta R_1 + A_{12}\Delta R_2 + A_{13}\Delta R_3 + A_{14}\Delta R_4 + A_{15}\Delta R_5; \\ \Delta R_{V2} = A_{21}\Delta R_1 + A_{22}\Delta R_2 + A_{23}\Delta R_3 + A_{24}\Delta R_4 + A_{25}\Delta R_5; \\ \Delta R_{V3} = A_{31}\Delta R_1 + A_{32}\Delta R_2 + A_{33}\Delta R_3 + A_{34}\Delta R_4 + A_{35}\Delta R_5; \\ \Delta R_{V4} = A_{41}\Delta R_1 + A_{42}\Delta R_2 + A_{43}\Delta R_3 + A_{44}\Delta R_4 + A_{45}\Delta R_5; \\ \Delta R_{V5} = A_{51}\Delta R_1 + A_{52}\Delta R_2 + A_{53}\Delta R_3 + A_{54}\Delta R_4 + A_{55}\Delta R_5. \end{cases} \tag{9}$$

where

$$A_{11} = \frac{\Delta R_{V1}}{\Delta R_1};$$

when $R_2 = const$, $R_3 = const$, $R_4 = const$, $R_5 = const$.

$$A_{21} = \frac{\Delta R_{V2}}{\Delta R_1};$$

when $R_2 = const$, $R_3 = const$, $R_4 = const$, $R_5 = const$.

$$A_{55} = \frac{\Delta R_{V5}}{\Delta R_5};$$

when $R_1 = const$, $R_2 = const$, $R_3 = const$, $R_4 = const$.

The experimental data allow to obtain the values of voltage and current in the circles of cathodes and screens with variable supports R1…R5, we can obtain the parameters A11, A21, …, A55.

4 Conclusion

This article reveals the idea of obtaining mathematical dependencies by replacing the physical processes of a plasma generator with an equivalent electrical circuit. The main processes: getting current-voltage characteristic, obtaining of functional dependences for the electrical equivalent circuit of plasma processes and getting a simplified mathematical model of the investigated system. The next step is a formation of a control law which ensures the functional stability of plasma process and maintain stable effect of the current.

The mathematical system of functional dependencies allows reveal the dependence and influence of the coefficients on the deposition process and give a possibility to develop a control law formation system based on these dependencies, which should ensure the functional stability of plasma formation and maintain a stable current effect.

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