Розроблено комплекс моделей динаміки і нелінійних систем управління всіма етапами іонно-плазмового нанесення покриттів на металорізальний інструмент. Імітаційне моделювання розроблених систем управління показало високу якість як програмно-керованих процесів, так і процесів, що стабілізують виділені технологічні параметри. Параметричний синтез використаних регуляторів вівся за компромісною методикою, що зв'язує робастність системи і швидкодію перехідного процесу при максимальних збуреннях

Ключові слова: нанесення покриттів, іонне бомбування, нелінійна система управління, металорізальний інструмент, конденсація речовини

Разработан комплекс моделей динамики и нелинейных систем управления всеми этапами ионно-плазменного нанесения покрытий на металлорежущий инструмент. Имитационное моделирование разработанных систем управления показало высокое качество как программно-управляемых процессов, так и процессов, стабилизирующих выделенные технологические параметры. Параметрический синтез использованных регуляторов велся по компромиссной методике, связывающей робастность системы и быстродействие переходного процесса при максимальных возмущениях

Ключевые слова: нанесение покрытий, ионная бомбардировка, нелинейная система управления, металлорежущий инструмент, конденсация вещества

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DESIGN OF A SET OF NONLINEAR CONTROL SYSTEMS OF THE ARC PVD ION-PLASMA INSTALLATION

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1. Introduction

The intensification of metal cutting equipment, as well as an increase in the complexity of machined parts, render relevance to the task on computer-integrated automation of equipment that would improve the durability and performance efficiency of tools.

One of the most universal units to increase the durability and performance of cutting tools work is the installation that employs cathodic arc deposition (CIB). That is a physical vapor deposition technique in which an electric arc (Arc-PVD) is used to vaporize material ions from a cathode target. The vaporized ions then condenses on a substrate, forming a thin film. The machined tool can be made of various materials; its durability and performance efficiency significantly improve after its treatment.

The application of coatings using the CIB method implies the following stages:

– a plasma flow of metal ions is formed employing a vacuum arc with the cold cathode;

– the flow is accelerated by applying a negative potential to the tool;

– the surface of the tool is cleaned by the intense bombardment of the surface with accelerated ions of the sprayed substance, thereby creating conditions for the high adhesion of the coating to the substrate;

– metal ions are condensed on the tool;

– a plasma-chemical reaction between the flow and a reactive gas is performed.

By feeding a gas-reagent into the vacuum chamber during the electric arc evaporation of a refractory metal, one can obtain coatings based on nitrides, carbides, and other compounds of metals from groups IV–VI. At a high potential of the substrate, not only the deposited metal is sprayed but also, partially, a surface layer of the substrate. The ion etching of the substrate is thus conducted, which enables cleaning of the surface. At the same, accelerated ions are embedded in the substrate and saturate the thin near-surface layer. The penetration depth of ions in this case is sufficient to ensure reliable adhesion of the coating. Thus, the technological process of applying a coating on the tool in the installation consists of three stages, performed sequentially: ion cleaning of the tool, applying a coating on the tool, tool cooling.

In paper [1], an author of the method gives a detailed overview of CIB technology and the history of its development. Although the physical fundamentals underlying a given technology have long been known, a technical solution that implements the technology instrumentally was first developed at the Kharkiv Institute of Physics and Technology (KhFTI, Ukraine) in the late 1970s. The patented technical solution has been sold to many countries around the world. It is noted that the disadvantage of both traditional and newly-designed installations is the low level of their automation. Therefore, at present, the development of quality systems for computer automation, as well as ensuring the independence of their work results of the operator's competencies, is an important task.

2. Literature review and problem statement

A fundamental study into automation systems for the installations of ion-plasma coating for metal cutting tools is described in paper [2] whose authors developed a number of models for all three stages of treating the tool, and the corresponding control systems. The disadvantage of a given work is the development and modeling of control systems using the linearized models of controlled objects at significant non-linearities in the behavior of actual controlled objects. In addition, not all of the control systems have been modeled.

There are several studies into improvement of local control systems of installations, similar by the principle of operation.

Paper [3] considers a system of computer automation that includes circuits for maintaining vacuum and temperature. A special feature of the work is that the authors measure a coating thickness. However, the stabilization of a coating thickness with a control system is not conducted. Regulating controllers are connected, via a USB interface, to a computer that performs basic computational functions and displays information. A shortcoming of the system is the use of sensors with the interfaces RS-232C and USB with converters between them. These interfaces enable signal transmission only over a short distance while the presence of intermediate converters reduces reliability of the system.

Paper [4] addresses automatic temperature and gas rate control systems in the chamber for chemical application of coatings using PID-controllers. The work, however, does not propose any comprehensive solution to control the installation.

Authors of [5] developed a system of control that maintains the arc voltage by changing the feed of a reaction gas. The system is experimental and is used to coat with aluminum oxide, which is not of interest in solving the considered task on coating a metal cutting tool.

Paper [6] considers a system of automatic control over an installation for applying a silver coating. Only the gas consumption is stabilized, fed to the installation, and a coating thickness. However, a growth in the coating thickness, when calculating a control system, is modeled in a very simplified manner, by a linear first-order model, without taking into consideration the physics of the coating application process.

Authors of [7] examined the dependence of coating quality on the constancy of application temperature. However, the study was conducted only for the installation for chemical deposition.

Paper [8] describes the effect of stabilized settings of the installations for applying the ion-plasma coatings on the target parameters of tools. Much to our regret, the dependences were described only qualitatively, the quantitative models are missing.

Paper [9] compares the work of PID and LQR controllers for the installation that applies nickel-copper-silver coatings. A simplified model of the controlled object is the same as described in [6]. It is shown that certain advantages in terms of transient processes are demonstrated by the system with a LQR-controller.

Authors of [10] describe an arc current control system using a PID-controller, adapted with the help of the fuzzified rules. The model of an arc is given in a simplified form as a linear differential equation of second order. The system is focused on maintaining the arc at welding.

Paper [11] gives a simplistic structure of the installation control system. Two control circuits are considered: the concentrations of gas in the chamber and rarefaction. The concentration and vacuum gauges are connected via the interface RS-232C; its disadvantages were described above. A distinctive feature of the system is a subsystem of remote control over the power modules of the installation, executed by a controller using the interface RS-485.

Authors of [12] argued about the urgent need to modernize installations for the ion-plasma application of coatings. Automation system was developed whose technical core is a panel PC with a touch screen. The authors described a computer interface of the automation system, oriented for an operator with limited experience of work at the installation. Control systems, however, were not described. There was only indicated that rarefaction, currents, and voltage are controlled; there is also an implemented system for feeding a reaction gas.

In [13], a new sensor was designed to monitor plasma emission, which enables fast reaction compared to inertial sensors used for indirect measurements. The sensor accuracy is compromised by the two circumstances. First, the line of plasma vision may be dimmed by the movement of the substrate. Second, the sensor in the process of work is covered with the deposited material.

Paper [14] attempts to perform a structural synthesis of an automated control system over the balance of gases-reagents, fed into a vacuum chamber, in the technology of ion-plasma coating application. The control system, however, was not developed.

Analysis of the scientific literature has revealed the following unresolved problems in the development of systems for automated control over the installation for ion-plasma application of coatings on metal cutting tool, based on CIB method:

– there are the results of research and development of separate subsystems in the installation, but there is no description of the results of research and development of the whole processes control system in the installation that are consistent with the requirements of technological regulations;

– development of almost all described control systems is based on the linearized models, which significantly degrades the quality of work of the designed systems in operation at an actual object that belongs to a class of essentially nonlinear ones;

– advances in mathematical and technical support for control systems in the last decade has made it possible to propose and implement a reduction in the deviation of regulated indicators of the installation, which would lead to the improvement of quality of coated tools;

– the need for an integrated improvement of control systems for the installation with an enhanced level of automation is also predetermined by a decrease, over recent years, in the professionalism of the installation operators.

3. The aim and objectives of the study

The aim of present study is to develop an integrated control system over the installation for applying ion-plasma coatings on metal cutting tools using a CIB method.

To accomplish the aim, the following tasks have been set:

– to develop and study a system of control over the ion cleaning of metal cutting tools from impurities at a programmed change in temperature until reaching a regulatory value when controlling the arc;

– to develop and examine control system over the application of ionic coating on tools at the stabilization of temperature and pressure in the installation's chamber when controlling voltage at the substrate and feeding nitrogen;

– to develop and explore control system over tool cooling at a programmed change in temperature until reaching a regulatory value when controlling nitrogen feed to the chamber.

4. Materials and methods of research

Research methods are the methods for modelling the dynamics of controlled objects, methods of the theory of automatic control, methods of simulation modeling of nonlinear systems.

The models for the dynamics of controlled objects are based on relations that describe physical phenomena in a controlled object. Because measurements of essential process parameters and introduction of controlling influences are performed at the characteristic places of the installation, we consider models with lumped parameters, based on the material and energy balances. The principle of modelling thermal processes corresponds to that described in paper [15]. Model validation was carried out according to the procedure described in paper [16]. The models belong to a class of essentially nonlinear systems.

Development of control systems is performed for nonlinear objects. Control system for the first task in our study differs significantly from other control systems. A given system should provide for a change in the controlled parameter in accordance with the specified linear program when using a relay control. Other systems employ limited continuous control; the quality of systems is measured by the rate of transition processes and the robustness of the control system. To simulate control systems and obtain transient processes when controlling by the program and to stabilize parameters under the influence of external disturbances, we apply the programming environment Matlab Simulink. To conduct simulation experiments on the application of coatings, we shall choose small tools with a cylindrical shape (drills, cutters, etc.), made of tool steel. A cylinder has length L, which is much larger than radius R.

5. Results of the development of control system over the installation for applying ion-plasma coatings on tools

5. 1. Development of control system over the installation at ion-plasma cleaning of tools

The ion-plasma cleaning of tools from dirt is performed in the process of ion bombardment of tool surface and its heating from the initial temperature to the temperature at which a coating is applied. In this case, it is necessary to avoid overheating of the tool and, consequently, defects.

Proper process of ion cleaning requires vacuum in the chamber and a high constant voltage at the substrate. Therefore, these settings cannot be controlled. However, one cannot change the arc voltage due to the design of the electric arc evaporator. Therefore, only the relay control over the arc is possible.

The heating of the tool occurs due to the ion bombardment heat fluxes q_{arc} and from the heated substrate q_{sub}; heat losses occur due to radiation q_{rad}. Then the total heat flux $q(\tau)$ is derived from relation:

$$q(\tau)=q_{arc}(\tau)-q_{rad}(\tau)+q_{sub}(\tau). \quad (1)$$

Heat flux q_{arc} is calculated [17] from expression:

$$q_{arc}(\tau)=j\cdot s\cdot\left(\frac{E_0}{\bar{z}\cdot e}+U_{sub}(\tau)\right), \quad (2)$$

where j is the ion current density, A/m^2; s is the surface area of an object, m^2; E_0 is the mean kinetic energy of ions, J; $\bar{z}$ is the mean multiplicity of ion charge; e is the charge of an electron, eV; U_{sub} is the substrate voltage, V.

Thermal radiation flux is defined by the Stefan-Boltzmann law:

$$q_{rad}(\tau)=s\cdot\varepsilon\cdot\sigma_0\cdot T^4(\tau), \quad (3)$$

where ε is the emissivity of the radiation surface; σ_0 is the emissivity of a blackbody (σ_0=0.576·10^{-7} W/m^{2}K^4).

Heat transfer from a heated substrate to the tool is defined by the Fourier law:

$$q_{sub}(\tau)=\alpha\cdot(T_{sub}-T(\tau)), \quad (4)$$

where $\alpha=7.9$ W/K is the experimental coefficient for steel, $T_п$ is the constant temperature of the substrate, K.

Then the total heat flux is equal to:

$$q(\tau)=j\cdot s\cdot\left(\frac{E_0}{\bar{z}\cdot e}+U_{sub}(\tau)\right)-$$
$$-s\cdot\varepsilon\cdot\sigma_0\cdot T^4(\tau)+\alpha\cdot(T_{sub}-T). \quad (5)$$

The equation that describes the dynamics of change in temperature takes the form:

$$c_{tool}\cdot\rho_{tool}\cdot V_{tool}\cdot\frac{dT(\tau)}{d\tau}=-s\cdot\varepsilon\cdot\sigma_0\cdot T^4(\tau)+$$
$$+\alpha\cdot(T_{sub}-T(\tau))+j\cdot s\cdot U_{sub}(\tau)+j\cdot s\cdot\frac{E_0}{\bar{z}\cdot e}. \quad (6)$$

Though heat capacity of steel c_{tool} is often taken to be constant, it nevertheless depends on temperature. To approximate this dependence for reference information, we used polynomial

$$c_{tool} = 3.63\cdot 10^{-4}\cdot T^2 - 5.23\cdot 10^{-2}\cdot T + 387. \quad (7)$$

A chart of change in heat capacity is shown in Fig. 1.

The rest of the model parameters accept the following values: ρ_{tool}=8,000 kg/m^3, ε=0.15, σ_0=0.576·10^{-7} W/m^2·K^4, j=10 A/m^2, E_0=65 eV, $\bar{z}=1{,}79$, e=1 eV.

The purpose of the automated control system is to enable high-quality cleaning of tools before applying a coating. Cleaning is provided by the burnout of impurities under a uniform increase in temperature to that close to the linear program over 1,800 s. A permissible deviation from the heating program is not larger than the preset value of ±25 K. The magnitude of deflection, on the one hand, is predetermined by the fundamentally relay character of control – enabling and disabling the arc, and, on the other hand, by the need to prevent a change in the structure of metal that the tool is made of.

At the initial stage, the arc is enabled and the heating-cleaning occurs. When the surface temperature reaches the value of the upper permissible limit for the current moment, the arc is disabled. Upon disabling, the tool cools at the expense of radiation energy loss. Enabling and disabling the arc continues until the measured surface temperature T is equal to the preset temperature for applying a coating T_{coat}.

A model of the control system is shown in Fig. 2; subsystems of the model are shown in Fig. 3. Charts of transitional processes are shown in Fig. 4, 5.

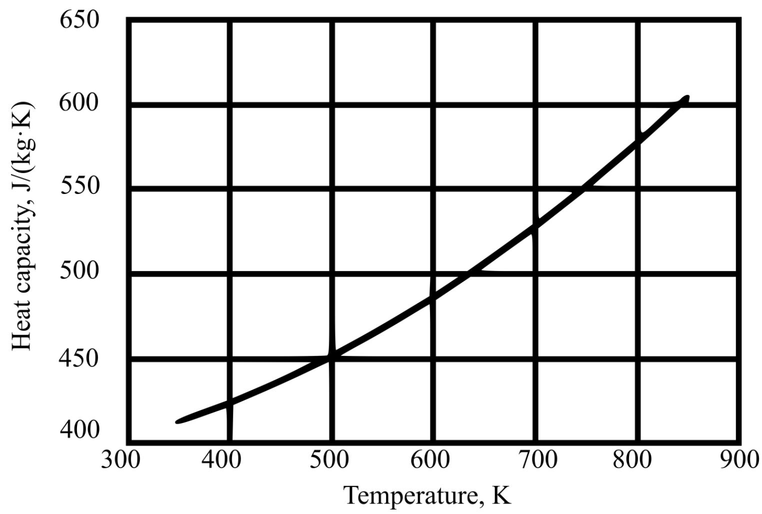

Fig. 1. Chart of change in the heat capacity of steel

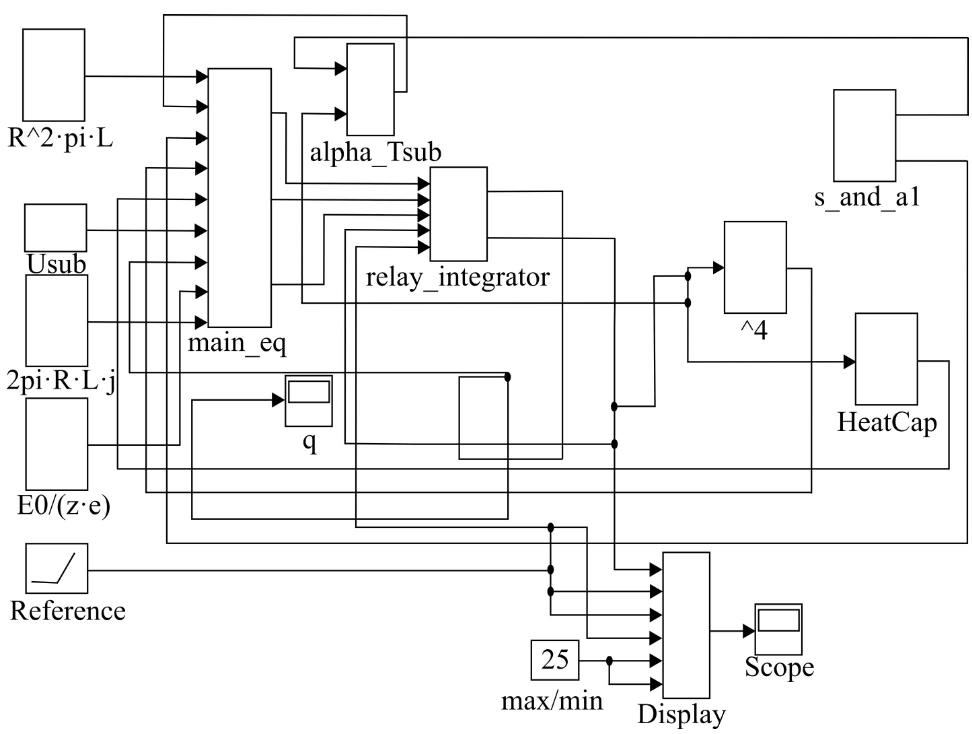

Fig. 2. Simulation model of the ionic cleaning control system

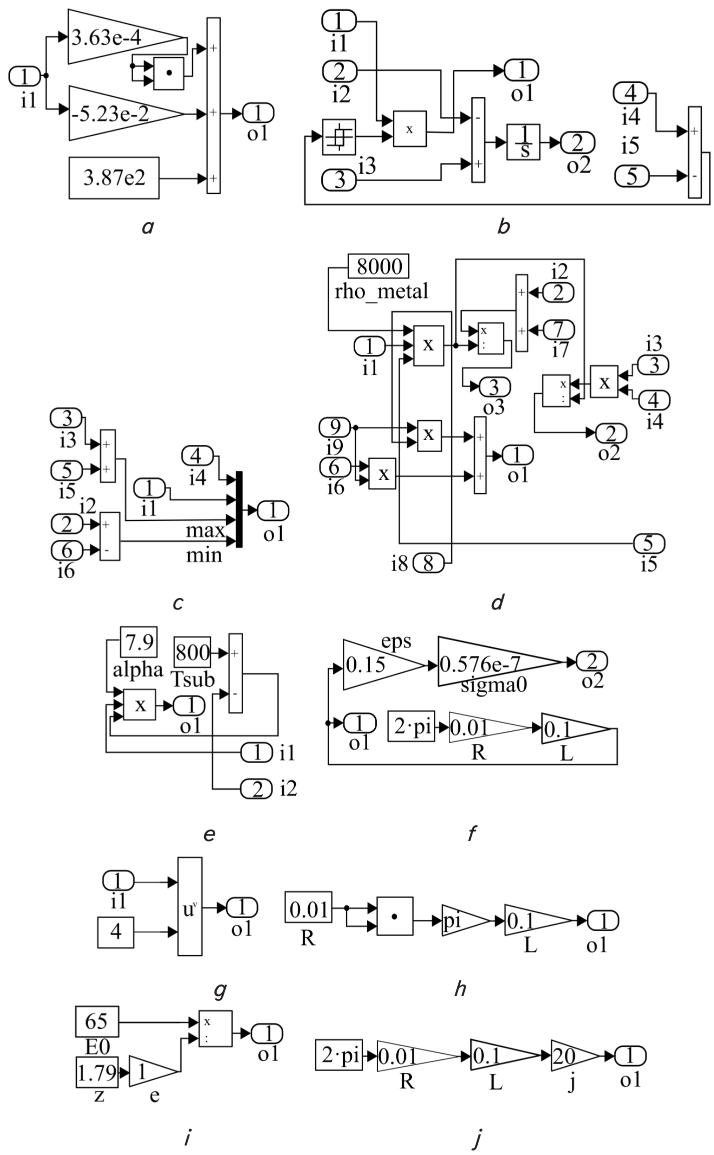

Fig. 3. Subsystems of the model (designations correspond to Fig. 2): *a* – HeatCup, *b* – Relay_Integrator, *c* – Display, *d* – main_eq, *e* – alfa_Tsub, *f* – s_and_a1, *g* – ^4, *h* – R^2*pi*L, *i* – E0/(z*e), *j* – 2*pi*R*j

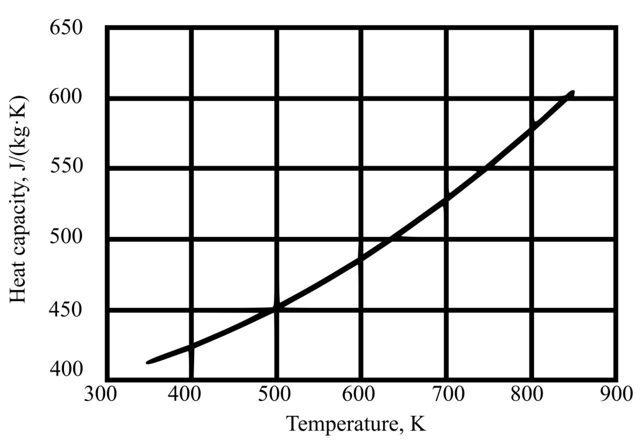

Fig. 4. Chart of a programmed change in the temperature of the tool at ionic cleaning

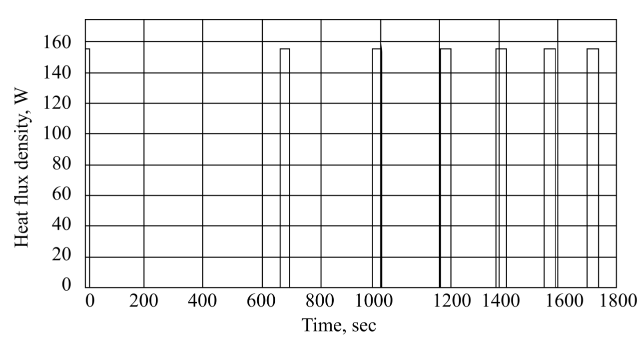

Fig. 5. Chart of change in control at ionic cleaning

An analysis of charts in Fig. 4, 5 shows that the purpose of control is achieved.

5. 2. Development of control system for the installation when applying the ion-plasma coating on tools

5. 2. 1. Control over thermal processes in tools

The purpose of control is to stabilize the temperature of tools in the process of coating application. Control is the substrate voltage $U_{sub}(\tau)$, measurement is the tool temperature $T(\tau)$, disturbance is the heat flux from the tool to the cartridge that holds it, q_c.

Similar to the previous case, a differential equation of the dynamics of tool heating in the coating application process takes the form:

$$c_{tool} \cdot \rho_{tool} \cdot V_{tool} \cdot \frac{dT(\tau)}{d\tau} = $$
$$= -s \cdot \varepsilon \cdot \sigma_0 \cdot T^4(\tau) - q_c(\tau) + j \cdot s \cdot U_{sub}(\tau) + j \cdot s \cdot \frac{E_0}{\bar{z} \cdot e} \quad (8)$$

at initial condition $T(0)=T_0$.

The model has the same parameters as before. Initial temperature is T_0=800 K. Constraint for control is $0 \le U_{sub} \le 400$ B, disturbance is within $0,2 \le q_c \le 2$ W.

Simulation model of the temperature stabilization system at the stage of applying a coating on the tool is shown in Fig. 6.

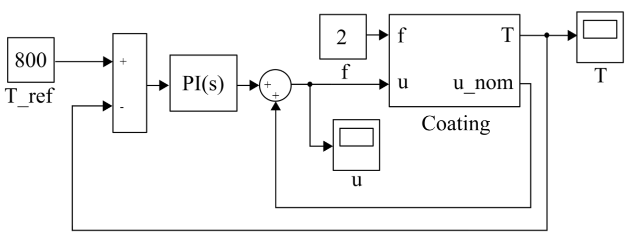

Fig. 6. Simulation model of the temperature stabilization system at the stage of applying a coating on the tool

Subsystem Coating of the stabilization system model is shown in Fig. 7.

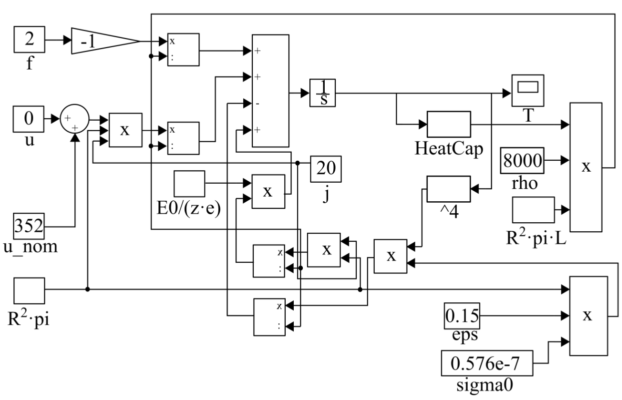

Fig. 7. Subsystem Coating

The model of subsystem Coating employs the subsystems given in chapter 5. 1.

We applied, as a subsystem PI(s), a standard PI-controller subsystem. The synthesis of the controller was conducted using the Simulink AutoConfiguration subsystem with a compromise of robustness and performance. The transfer function of the controller takes the form:

$$\mathrm{PI}(s) = 10.1 \cdot \left(1 + \frac{35.57 \cdot 10^{-5}}{s}\right). \quad (9)$$

Transient process of change in the tool temperature under the action of maximum disturbance is shown in Fig. 8, and the process of change in the controlling action – in Fig. 9. The course of the transient process ends at moment τ=1,000 s, which is marked by a dotted line. The next course is shown in order to demonstrate stability of the system. Upon completion of the process, a transition to the stage of cooling occurs. The quality of control system functioning is not affected by the incomplete course of the transition process, because a temperature deviation from the modal value is extremely low (0.3 K).

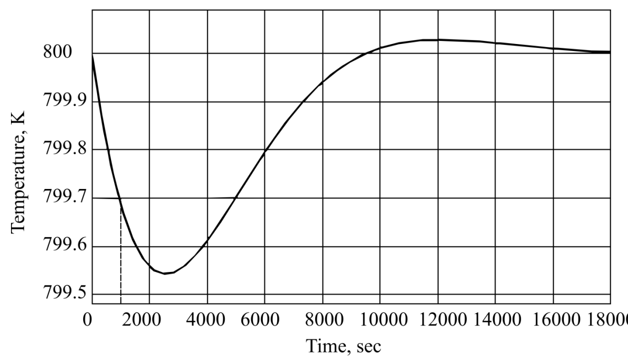

Fig. 8. Transient process of change in the tool temperature under the action of maximum disturbance

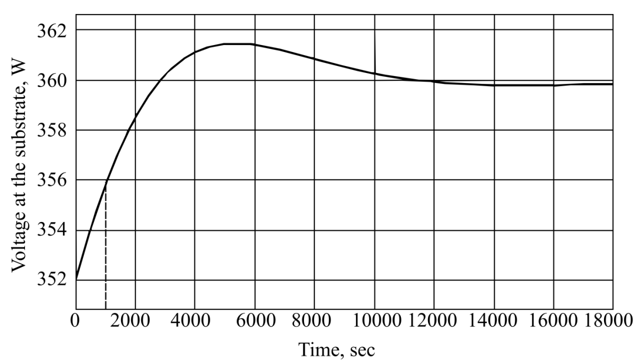

Fig. 9. Transient process of change in the controlling action

An analysis of the transient processes revealed that at a maximum disturbance the quality of temperature stabilization is high; the transient process duration is acceptable; controlling influence does not exceed the limits.

5. 2. 2. Control over pressure in a vacuum chamber

The purpose of control is to stabilize nitrogen pressure in the vacuum chamber in the coating application process. Controlling influence is the nitrogen feed, a measured parameter is pressure, deviation in the rates other flows is the disturbances.

To build a dynamic model of change in the nitrogen pressure in a vacuum chamber, we shall write a material balance:

$$\frac{dM_{N_2}}{d\tau} = m_p + m_n - m_o - m_{Ti}, \quad (10)$$

where M_{N_2} is the mass of gaseous nitrogen in a vacuum chamber, kg; m_p is the supply of nitrogen by its forced delivery to the chamber, kg/s; m_n is the supply of nitrogen with air inleakage from the atmosphere due to leaks in the chamber, kg/s; m_o is the nitrogen consumption due to work of a vacuum pump, kg/s; m_o is the nitrogen consumption for chemical reactions in the chamber, kg/s.

Assuming the volume of a vacuum chamber and gas temperature in it constant, we shall record based on the Mendeleev-Clapeyron law:

$$M_{N_2} = \frac{\mu_{N_2} \cdot V_c}{R \cdot T_c} \cdot P_{N_2}, \qquad (11)$$

where μ_{N_2} is the molecular weight of nitrogen ($\mu_{N_2} = 28$); V_c is the volume of the vacuum chamber, m^3; R is the universal gas constant (R=8.314 J·g-mol/K); T_c is the temperature of a gas mixture in a vacuum chamber, K; P_{N_2} is the partial pressure of nitrogen, Pa.

The massive arrival of nitrogen with air inleakage from the atmosphere due to the leakage of the chamber within one cycle of applying is a constant magnitude, equal to:

$$m_n = 0.79 \cdot \frac{\mu_{N_2} \cdot H}{R \cdot T_k}, \qquad (12)$$

where 0.79 is the share of partial pressure of nitrogen in the air; H is the inleakage, $m^3 \cdot Pa/s$.

Mass nitrogen consumption for the work of a vacuum pump is derived from expression:

$$m_o = \frac{\mu_{N_2} \cdot v_n}{R \cdot T_c} \cdot P_{N_2}, \qquad (13)$$

where v_n is the volumetric vacuum pump capacity, m^3/s.

Mass nitrogen consumption for chemical reactions in the chamber can be calculated based on chemical reaction $2Ti+N_2=2 \cdot TiN$, using formula:

$$m_{ch} = m_{Ti} \cdot \frac{0.5 \cdot \mu_{N_2}}{\mu_{Ti}}, \qquad (14)$$

where m_{Ti} is the mass of titanium used in one cycle of application, kg; μ_{Ti} is the molecular weight of titanium (μ_{Ti}=48).

Next, we can record a differential equation in the form:

$$a_1 \cdot \frac{dP_{N_2}(\tau)}{d\tau} = -a_2 \cdot P_{N_2}(\tau) + m_p \cdot (\tau) - a_3 \cdot m_{Ti}(\tau) + a_4, \qquad (15)$$

where

$$a_1 = \frac{\mu_{N_2} \cdot V_c}{R \cdot T_c}, \quad a_2 = \frac{\mu_{N_2} \cdot v_n}{R \cdot T_c},$$

$$a_3 = \frac{0.5 \cdot \mu_{N_2}}{\mu_{Ti}}, \quad a_4 = 0.79 \cdot \frac{\mu_{N_2} \cdot H}{R \cdot T_c},$$

and initial condition

$$P_{N_2}(0) = P_{N_2,0}.$$

Parameters that are included in the model accept the following values: $\mu_{N_2} = 28$ g; $\mu_{Ti} = 48$ g; V_c=0.16 m^3; T_c=300 K; R=8.314 J·mol/K; v_n=0.2 m^3/s; H=26.66·10^{-6} $m^3 \cdot Pa/s$.

Boundaries of change in control are

$$1 \cdot 10^{-3} \le m_n \le 6 \cdot 10^{-3} \text{ g/s},$$

in disturbances –

$$4.0 \cdot 10^{-3} \le m_{Ti} \le 5.5 \cdot 10^{-3} \text{ g/s}, \ (0.9\text{–}1.1) \cdot a_4.$$

A model of the control system is shown in Fig. 10. The subsystems used in the model are in Fig. 11.

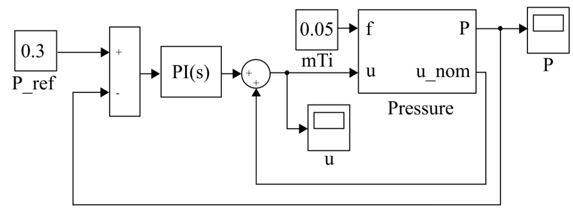

Fig. 10. Simulation model of the pressure control system

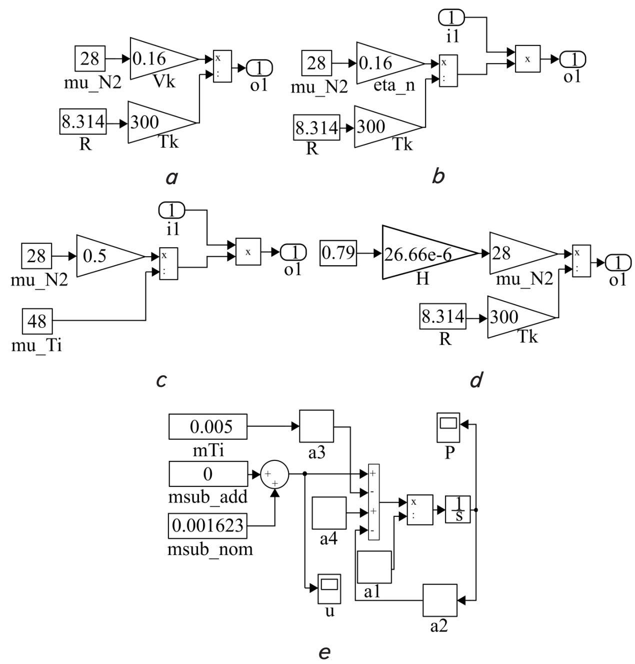

Fig. 11. Subsystems of the model for a pressure control system: *a* — subsystem a1; *b* — subsystem a2; *c* — subsystem a3; *d* — subsystem a4; *e* — subsystem Pressure

We applied, as a PI(s) subsystem, a standard PI-controller subsystem. The synthesis of the controller was conducted using the Simulink AutoConfiguration subsystem with a compromise of robustness and performance. The transfer function of the controller takes the form:

$$PI(s) = 0.01 \cdot \left(1 + \frac{3}{s}\right). \qquad (16)$$

Transient process of change in the tool temperature under the action of maximum disturbance is shown in Fig. 12; the process of change in the controlling influence – in Fig. 13.

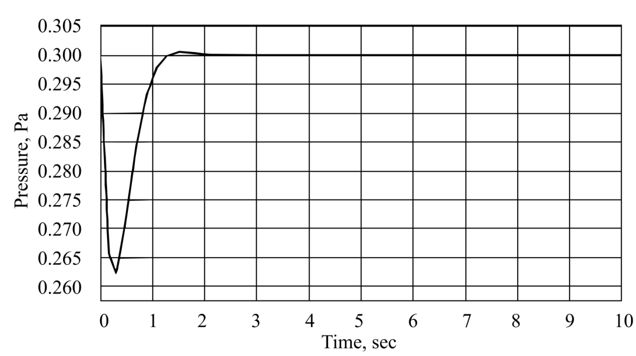

Fig. 12. Transient process of change in the nitrogen pressure under a disturbance by increasing mTi

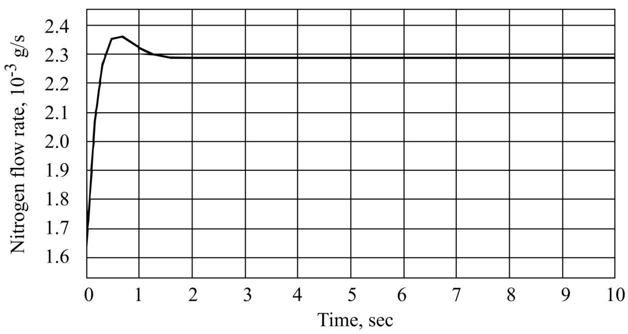

Fig. 13. Transient process for controlling influence

An analysis of transient processes revealed that at a maximum disturbance the quality of temperature stabilization is high; the transition process duration is acceptable; controlling influence does not exceed the limits. Thus, performance of the developed control system can be considered satisfactory.

5. 3. Development of control system for the installation at the stage of cooling

A signal about the onset of tool cooling in vacuum comes from the timer that counts the time for applying a coating τ_{coat}. Upon receiving a signal, work of the electric arc source is disabled; tool cooling occurs due to the infrared radiation and heat transfer into a supporting cartridge.

The heat exchange equation takes the form:

$$a_1 \cdot \frac{dT(\tau)}{d\tau} = -a_2 \cdot T^4(\tau) - q(\tau). \qquad (17)$$

The installation finishes work when the tool reaches temperature T=500 K. The chamber is depressurized and the tools are unloaded.

A circuit of the model of the cooling control system is shown in Fig. 14; the subsystem speed – in Fig. 15. We applied, as a PI(s) subsystem, a standard PI-controller subsystem. The synthesis of the controller was conducted using the Simulink AutoConfiguration subsystem with a compromise of robustness and performance. The transfer function of the controller takes the form:

$$\mathrm{PI}(s) = -11.34 \cdot \left(1 + \frac{0.0001}{s}\right). \qquad (18)$$

Transient process of change in the tool temperature in line with the program is shown in Fig. 16; the process of change in the controlling influence – in Fig. 17. Cooling rate is shown in Fig. 18.

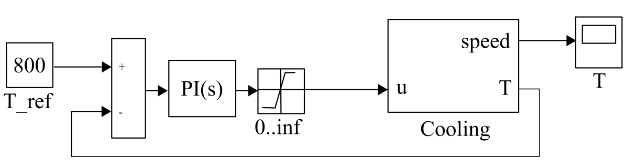

Fig. 14. Simulation model of the cooling control system

Charts in Fig. 16–18 show that the cooling process is satisfactory.

An analysis of transient processes revealed that the program of tool cooling is performed with high quality; controlling influence and the rate of cooling do not exceed the limits. Thus, performance of the developed control system can be considered satisfactory.

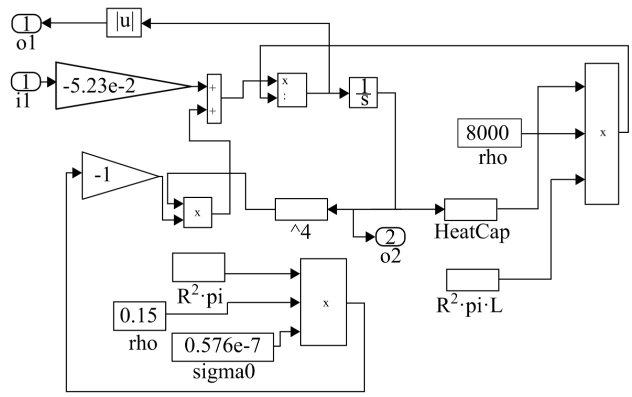

Fig. 15. Subsystem Cooling

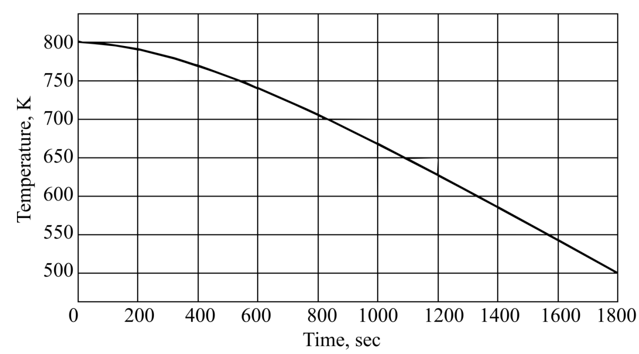

Fig. 16. Process of the programmed change in the tool temperature

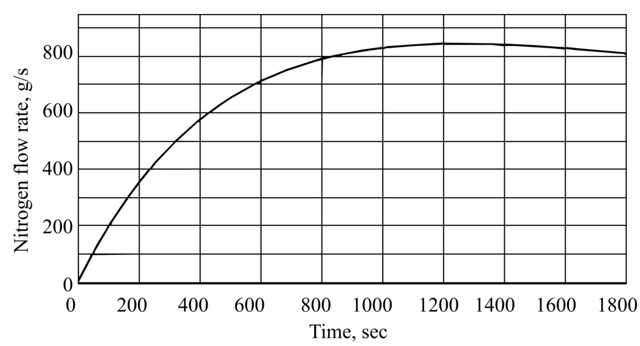

Fig. 17. Transient process of change in control at the stage of cooling

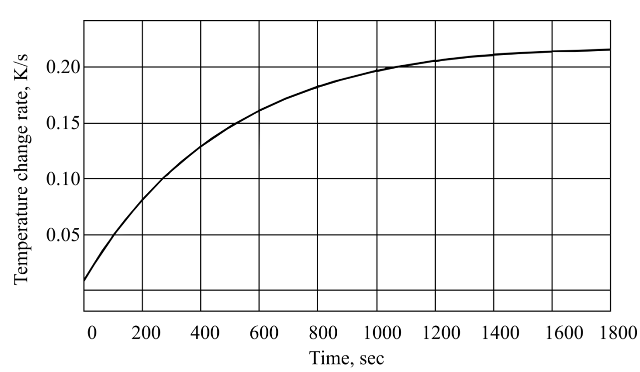

Fig. 18. Transient process of rate in the change of temperature at cooling

6. Discussion of results on the development of control system over the installation for the ion-plasma application of coatings

High-quality functioning of control system over the installation for the ion-plasma coatings is achieved by using the developed adequate nonlinear models of basic technological processes. Structural diagrams of the models are shown in Fig. 2, 3, 7, 11, 15.

Since the launch of the industrial installation for the ion-plasma spraying of coatings "Bulat-3", there have been designed more than fifteen modifications, some of which are given in paper [18]. The installations are currently produced as a small series, and to order. However, the automation of the installations has not been achieved in terms of improvement of control over a technological process, nor in terms of creating computer systems to monitor the status of the installation, nor the ease of manual control.

Paper [19] described the main characteristic of the tool, obtained as a result of spraying a coating at one of the latest modifications of the installation, namely, its resistance, which amounted to 36 minutes. By using a formula given in [20], we shall calculate resistance of the tool depending on the parameters of the modeled technological process – pressure P, Pa; temperature T, K; and the time τ, s, spent in the ionization chamber. Then, the tool resistance is derived from formula

$$C = 0.12\cdot\sigma\cdot 10^{-6} + 1.31\cdot H + 4.24\cdot\delta =$$
$$= 0.12\cdot 4.30\cdot 10^{-1} + 1.31\cdot 31.72 + 4.24\cdot 6.78 = 74.24 \text{ min},$$

where the adhesion with a coating σ is equal to

$$\sigma = 4.3\cdot 10^{5} - \left(10^{5}\cdot\left(3.1\cdot 10^{-3}\cdot(T-786)\right)^{2}\right)\cdot\left(2-e^{0.19\cdot P}\right) =$$
$$= 4.3\cdot 10^{5} - \left(10^{5}\cdot\left(3.1\cdot 10^{-3}\cdot(T-786)\right)^{2}\right)\cdot\left(2-e^{0.19\cdot 0.3}\right) =$$
$$= 4.30\cdot 10^{5} \text{ Pa=0.43 MPa},$$

the tool microhardness is

$$H = 32 - \left(1\cdot 10^{-4}\cdot\left(800-728\cdot(1+0.08\cdot P)\right)^{2}\right)\cdot\left(2-e^{0.22\cdot P}\right) =$$
$$32 - \left(1\cdot 10^{-4}\cdot\left(800-728\cdot(1+0.08\cdot 0.3)\right)^{2}\right)\cdot\left(2-e^{0.22\cdot 0.3}\right) = 31.72, \text{ GPa},$$

the thickness of a tool coating is

$$\delta = 1.111\cdot 10^{-9}\cdot\tau\cdot\left(7.2-e^{0.32\cdot P}\right) =$$
$$= 1.111\cdot 10^{-9}\cdot 1000\cdot\left(7.2-e^{0.32\cdot 0.3}\right) = 6.78\cdot 10^{-6}, \text{ m}.$$

Thus, the use of the developed control system made it possible to significantly improve the resistance of tools compared to the installations that are currently applied. In addition, at ionic cleaning, we managed to achieve a temperature deviation from the programmed value of 5 K instead of the standard 25 K, which also helps to improve the quality of the treated instrument, thereby reaching the level of defects equal to one point.

Given the introduction of a large variety of modifications of installations, as mentioned above, it is expedient to consider issues related to the automation of development of control systems for the installations of a given type with different parameters. In addition, our study does not address issues on the program-technical realization of a control system that can impose a limitation on the application of results related to the adequacy of choosing sensors with enhanced accuracy to measure technological parameters.

We plan to undertake further research aimed at coordination of the program-technical and the developed conceptual structure of control systems for the installations of a given type.

7. Conclusions

1. First control system over the process of ionic cleaning of tools in the ionic-vacuum installation for applying coatings on metal cutting tools is developed and studied. A temperature rise of the tool over the specified time, which defines the quality of cleaning, is maintained at the preset linear program by enabling and disabling the arc discharge. We managed to keep the exactly specified time for the ionic cleaning equal to 1800 s, with a deviation in temperature from the assigned program not exceeding 25 K when the temperature increased from 300 K to 800 K.

2. Second control system over the process of applying a coating on tools in the ion-vacuum installation is developed and examined. The stabilization of temperature of the tool is carried out applying a continuous change in voltage at the substrate. The stabilization of pressure in the vacuum chamber is maintained by changing the flow rate of nitrogen into the chamber. Deviation in the temperature of tools when applying a coating and under the action of maximum disturbance by deviating a heat flux by 2 W is 0.5 K at the rated 800 K. Deviation in the pressure of nitrogen at a maximum deviation in the flow rate by $5.5\cdot 10^{-3}$ g/s is less than 0.04 Pa.

3. Third control system over the cooling of tools in the ion-vacuum installation is developed and studied. The cooling of tools from 800 K to 500 K is performed by changing a feed of nitrogen into the chamber. We managed to keep the exact preset cooling time of 1800 s at a temperature change rate not exceeding 0.22 K/s and a nitrogen flow rate to 850 g/s.

4. Fourth control system for the entire complex of the ion-plasma installation for applying coatings on metal cutting tools applying a CIB method is developed and examined. Coordinated work of subsystems with the presented deviations in technological parameters ensures high quality and durability of tools. The system can enable the operation of the installation under automated mode.

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