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ANALYSIS OF THE HEAT PROCESSES OF FORMING THE ALUMINIDE COATING ON THE GAS TURBINE BLADES

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The rotor blades of gas turbine engines (GTE) are produced from the nickel heat-resistant alloys, in combination with embodiment determining the admissible temperature of working gas before turbine; this temperature has impact on the engine principal characteristics, such as thrust, economic efficiency, resource, etc. nevertheless, these alloys do not guarantee the sufficient resistance to the impact of the aggressive medium of engine gas flow. The temperature in the interaction zone of saturating elements and the product basis in the course of forming the nano-coatings of gas turbine blades is one of the main factors determining the chemical and phase composition of surface layers and consequently the physical and mechanical properties and performance of alloys with coatings [1]. The paper presents the general mathematical model (MM) of one-dimensional thermal conductivity in multi-layer system of heterogeneous layers of spade covering, the lines of which relocate in time; the model comprises the general differential equations of thermal conductivity specified for every layer of the system, the terms of thermal contact of every pair of connected layers (equity of temperatures and thermal flows), and the terms of heat exchange on the outer edging surface of the system and the conditions of temperature distribution within the system before the beginning of every process stage.

Keywords: gas turbine, turbine blade, heat-resistant alloy, aluminide coating, mathematical model of the heat processes of coating formation

1. Introduction

High-temperature oxidation of heat-resistant nickel alloys in combination with sulphide and vanadic corrosion sufficiently limits the resource of gas-turbine blades. Employment of protecting coatings allows prolonging their life span by 3…5 times. Despite the great variability of technological schemes of receiving the heat-resistant coatings (diffusive, condensation or combined from them), Al, Si, Cr are still the main components creating the surface membrane on the protected detail; these components exist in saturating medium in one form or another [2].

One of the ways of increasing the heat-resistance of steels and alloys is employment of diffusion protective coatings. It is known that the temperature in zone of interaction of saturating components and product basis in the process of forming the coating is the main factor, determining the chemical and phase composition of surface layers (under the condition of specified composition of saturating medium) and physical and mechanical properties and performance of steels and alloys [3].

Another procedure is implemented for forming the coating with an employment of suspension with heating in the air as a saturating medium. The process of saturation from suspension (aluminising and aluminium-silicification) with heating in the air [4] determines the temperature terms on the allotment line between contacting mediums not only in accordance with furnace isotherm, but also with detail size, unit weight of the suspension deposition on the sample surfaces. It results in the necessity of developing the mathematical model of heat process of forming the coatings aimed at choosing the optimal modes and adjusting the properties of obtained protective layers.

The goal of problem solving is facilitating the adequacy of mathematical description of generalised heat process of coating forming from suspensions by introducing the members to the model; these members take into account the additional physical and thermodynamic processes of layer forming and heat-generation to accumulating coating by means of oxidising the hydrogen emitted from the hydrogen suspension deposition in the process of samples heating.

2. Development of Mathematical Model of Forming the Coating

The procedure of thermal task assigning within the system "coating – basis" with moving border lines demands the solution of the set of equations of unstable thermal conductivity; moreover the law of border line movement and conditions are specified by certain physical processes.

The employed mathematical models (MM) do not consider these processes [4, 5], since these models, first, do not take into account inner heat release, and second, only outer border line is moving, for instance, at plasma applying the coatings [4]. Moreover, opposed to the provided researches, solving the tasks with specified law of moving border lines (border lines conditions of the forth type), the task under consideration stipulates assigning the reasons (namely phase transformation), specifying the movement of inner border lines. The laws of this movement are the part of required properties of the process.

Therefore the considered task presents an attempt to create the model with special border lines conditions (BLC), which can be named by analogy with [4, 5] the BLC of the fifth type. Thereby the calculations of complex multilayer system simultaneously employ the BLC of lower type.

The scheme of calculation of the system "suspension – coating – basis" is presented on Figure 1.

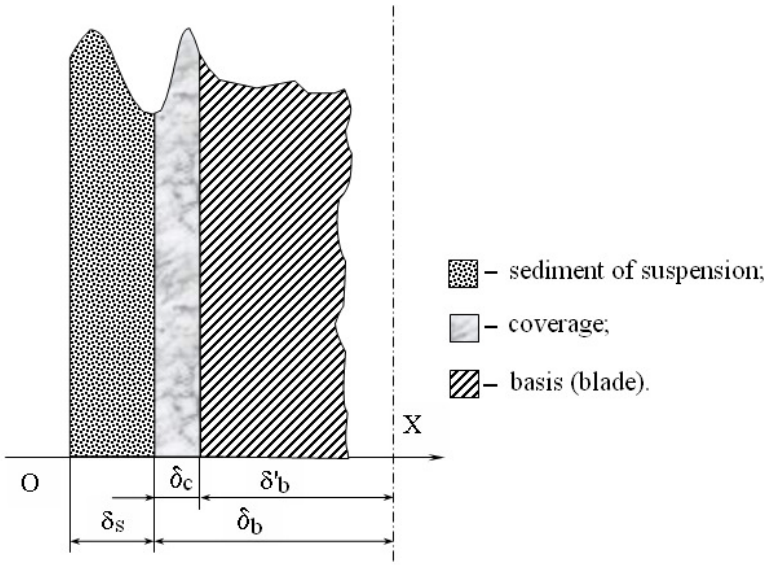

Figure 1. Scheme of borders of interacting mediums in the process of saturation from suspensions

Since the body thermal expansion and compression are not taken into consideration, the specified system can be written in the following form:

$$\delta_S + \delta_b = \delta_S + \delta_C + \delta_b' = const\ , \tag{1}$$

where δ_S is suspension layer depth; δ_b and δ_b' are the sample body thickness before and in the process of coating applying; δ_C is the depth of generating coating.

Under these conditions the coordinates of intermediate layer (equation of coating lines movement) are found by the formulae as follows:

$$X_S = \delta_C;\ \ X_C = \delta_S + \nu\tau\ , \tag{2}$$

where τ is the time of process; ν is the velocity of border lines movement (it is considered below).

Hence it appears that the coating depth is determined by

$$\delta_C = X_C - X_C = v\tau\ . \tag{3}$$

Opposed to the border lines conditions of the forth type [4], when the law of border lines movement (velocity of their movement v), the considered task (at specified stage) assigns, as it has been demonstrated above, the inner BLC of the fifth type in the form of law of temperature changing on the basis of heat release within the reaction of hydrogen combustion $T_B = f(\Delta\tau_{II})$ (see Fig. 2).

Then the velocity of border lines movement is determined as follows:

$$v = f'(T_B) = f'\left[f(\Delta\tau_{II})\right]. \tag{4}$$

This velocity is supposed to be variable depending on the disposable difference of temperatures (ΔT_h) on the border of suspension and coating layers (see Fig. 2)

$$v = \frac{\Delta T_h / T_{S\max}}{\Delta T_{\max} / T_B}\left(\frac{dx}{d\tau}\right)_{av} = \frac{(T_S - T_H)/T_{S\max}}{(T_0 - T_H)/T_B} \cdot \frac{\delta_{C(F)}}{\Delta\tau_{MB}} = f(T_B, T_S). \tag{4a}$$

The final depth of coating layer $\delta_{C(F)}$ is determined from the experimental slices of samples, and time of movement of moving border line is $\Delta\tau_{MB} = \tau_{III} + \tau_{MB}$.

Hydrogen combustion temperature $T_B = f(\tau_{II} - \tau_I) = f(q_V)$ is specified at a first approximation basing on the value of released heat q_V under the condition of specified chemical reactions in suspension of proposed composition. The value of heat q_V depends on the composition and mass of suspension, the initial temperature in the furnace and, correspondingly, the amount of released hydrogen.

The set of equations in MM, considered below, is supposed to be sectionally isotropic and sectionally homogeneous relatively to the properties influencing the process of thermal conductivity. It does not suppose the constant thermal-physic properties of a certain layer, but only indicates their dependence on the thermal state of the system components (layers) only. That is why the thermal-physic properties of every layer (the thermal conductivity coefficient λ, unit mass heat capacity C_m and density ρ) in the general case are supposed to be dependent on the temperature.

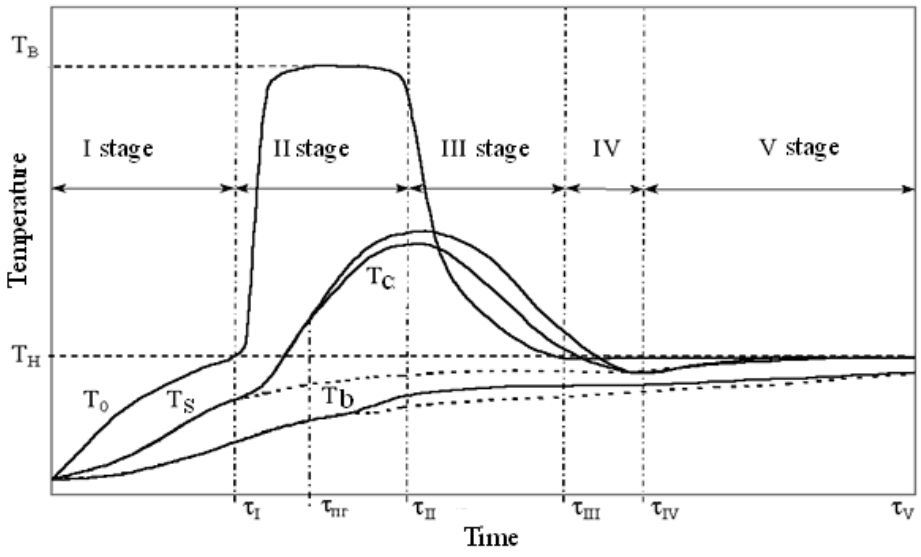

Figure 2. Temperature change on the system border lines at different process stages

The dependence of thermal-physic coefficients in a rather wide temperature range can be presented as a linear model for many polycrystal bodies:

$$\lambda_i(T_i) = \lambda_0(1 + \varepsilon_{\lambda i} \cdot T_i); \tag{5}$$

$$C_i(T_i) = C_0(1 + \varepsilon_{Ci} \cdot T_i), \tag{6}$$

where $C_i(T_i) = C_m(T_i) \cdot \rho(T_i)$ is a volumetric heat capacity.

The introduced parameter ε works as a minor parameter for solving the set of equations in MM by perturbation theory method. If $\varepsilon = a$ for the specified material, the solution of the equations system corresponds to the required solution.

If $\varepsilon = 0$, the solution of the system corresponds to the same materials but with certain coefficients not depending on the temperature for the so-called unperturbed problem (zero-order approximation).

The restrictions, similar to the above mentioned ones for the layers of initial system, are implemented for the properties of generating coating. It is supposed that the variability of the system border lines has no impact on the nature of dependencies of thermal-physic properties of every layer on the temperature.

The initial temperature field at every stage within every layer and within the system in general typically heterogeneous and it is specified by segmentally differential functions by separate time spans, considered above (see Fig. 2). The distinctive feature of this task is, opposed to [4, 5], the fact that there is a source and correspondingly the outflow of the heat to the outer environment (by convection and radiation) within the system.

There is calculation of specified unstable border lines conditions of general type. They comprise as particular cases the traditional conditions of the first, the second and the third types (correspondingly, joining on the border lines and specified alterations on time-dependant temperatures, heat flows and conditions of interacting with the outer environment). These conditions can be different at different stages (under the condition of maintenance of the specified dimension of problem).

Besides setting the regularity of temperature changes in the process of coatings applying the goal of MM is also an elaboration of the estimation criteria for the structure of generating coating (with regard to the modelled process) on its basis and determination of their dependencies on total time of the sample staying in the thermal medium. This total time, concerning the developed MM, is separated into the range of particular stages.

These stages basing on the estimation of the thermal-physical processes can be presented in the following consequence (see Fig. 2):

I stage – a sample heating (blades with applied suspension) in the thermal medium before beginning the released hydrogen ignition;

II stage – hydrogen combustion, melting the suspension components, deposition of melt on the surface of padding; dilution of the basis in the melt is accompanied by the movement of border line of inter-phase at the middle of the stage;

III stage – ceasing the hydrogen combustion simultaneously with continuing applying the coating and its crystallising;

IV stage – solid-phase diffusion in the invariable coating layer with possible re-crystallisation;

V stage – alignment of the temperatures within the sample layers.

The aim of the experimental investigation which is preliminary for the MM development, regarding the considered model was in obtaining the specified structure of the coating depending on the temperature of the medium (temperature in the furnace) under the condition of minimising the time of the first four stages.

At the first stage of an experiment the sample having the temperature T_0 in all points at a certain initial moment of time $\tau = 0$ was placed into the furnace with the temperature T_H (where $T_H = \text{const}$).

The sample heating can be demonstrated in the following succession. First, there is transition of heat from the heating medium to the surface layer of the body – suspension, and then heat distribution from the surface layer inside the sample.

Suspension heating follows the laws of convective heat exchange, and transmission of heat inside the sample follows the laws of thermal conductivity.

Figure 2 demonstrates the qualitative curves of temperature change of elements volumes located on the layers surfaces: suspensions on the outer (T_0) and inner (T_S) border lines, coating on the inner (T_C) variable border line and in the centre of the sample (T_b). Specification of particular quantitative dependencies of temperatures on time is the subject of this research. At the same time the qualitative specification of gradients of temperatures allows correct composition of equation system in MM, namely to specify the direction of heat flows and nature of heat exchange (the type of heat transfer – for instance, convection or radiation).

Thus, in the beginning of the first stage of heat exchange the value of heat flow, coming from the surrounding medium into the suspension surface layer is determined by Newton equation for convective heat exchange:

$$q_a = \alpha(T_H - T_0), \tag{7}$$

where α is a coefficient of heat emission.

This value has the biggest magnitude at the first moment of heating when the difference of temperatures $T_H - T_0$ is the biggest one (see Fig. 2); then the value q_a monotonously diminishes asymptotically tends towards zero ($T_H - T_0 = 0$). This value $q_a = 0$ corresponds to the end of stage I.

The value of heat flow, coming from the surface layer inside the sample massive (body), is determined by Fourier equation for thermal conductivity:

$$q_l = -\lambda_i(T_i) \cdot dT/dx\,. \tag{8}$$

This value reaches the biggest magnitude at the moment when $\Delta T = T_b - T_0 = \max$.

At every moment of time the heat flows q_a and q_1 are not equal to each other, which is typical for unstable heat exchange. Nevertheless, at every moment there is an equation in the surface layer of suspension:

$$\alpha \cdot (T_H - T_0) = -\lambda_1(T_i) \cdot dT/dx. \tag{9}$$

This equation of heat flows is maintained on the border line of the outer environment and a solid body, being the border line condition of the second type.

Specification of the law of coefficient α change is the border line condition of the third type. Since in the considered case the sample is not subjected to the outer flow (α mainly depends on the velocity of movement of outer heat-transfer agent), but is located into unmovable medium, at first approximation it is considered $\alpha = \text{const}$.

The difference of heat flows via the unit of surface within the layer facilitates an increase of inner energy of substance volume, namely increase of its temperature. As a result the temperature field in any section will change so that the temperature curves $T = f(x)$ will deform in time.

For inner volume of elements of every layer the thermal conductivity equation, setting the connection between the temporary and spatial temperature change at any section point of the system body, where (at the first stage) there is no phase transfers and inner sources of heat, can be expressed (under the condition of one-dimensional gradient of temperatures and heat flows) as $dU = dQ$ or

$$C_i(T_i)\frac{\partial T_i}{\partial \tau} = \frac{\partial}{\partial x}\left[\lambda_i(T_i)\frac{\partial T_i}{\partial x}\right] = \lambda_i(T_i)\frac{\partial^2 T}{\partial x^2}\,. \tag{10}$$

This equation is the first equation of mathematical model of the first stage. Other equations present the border lines conditions (joining the parameters at the layers border lines).

The condition on the outer border line is equation 9. The border line conditions of the first and the second type, being on the border line between the layer of suspension and the sample material ($x = \delta_S$), can be presented (for temperatures and heat flows) as:

$$T_1(0,\tau) = T_3(0,\tau)\,; \tag{11}$$

$$\lambda_1(T_1)\frac{\partial T_1}{\partial x} = \lambda_3(T_3)\frac{\partial T_3}{\partial x}\,. \tag{12}$$

The mathematical model of stage I includes also the border line conditions of the first and the second type on the suspension outer surface ($X = 0$) and sample central layer ($X = \delta_S + \delta_b$):

$$T_0 = T_b \text{ if } \tau = 0; \tag{13}$$

$$T_0 = T_H \text{ if } \tau = \tau_1; \tag{14}$$

$$q_a(T_1,\tau) = \lambda_1(T_1)\,\delta T_1/dx; \tag{15}$$

$$q_1(T_3,\tau) = \lambda_3(T_3)\,\delta T_3/dx. \tag{16}$$

At the first stage the solution is determination of the temperature field (values T_S and T_b), when the temperature changes along the *X* axis as

$$\frac{\partial T_i}{\partial \tau} = a_i(T_i)\frac{\partial^2 T_i}{\partial x^2} \tag{17}$$

and reaches the value $T_0 = T_H$ if $\tau = \tau_1$ on the sample surface.

In expression (17) $a_i(T_i) = \lambda_i(T_i)/C_i(T_i)$ is a coefficient of thermal conductivity.

Stage II is the most complicated one in the considered MM; the source of heat emission starts its activity as a result of hydrogen oxidation. Under this circumstances the difference in heat value emitted in the process of hydrogen combustion dQ_t and heat value flowing out via the surface of control volume dQ_f facilitates the increase of internal energy and accordingly the temperature in the emitted volume $dU = dQ_t - dQ_f$.

There are phase transfers in the generating layer of coating at certain temperature. Then the equation of change of density of internal energy is as follows:

$$dE = dU + dE_P = dQ_t - dQ_f.$$

The mathematical model of one-dimensional thermal conductivity in the multi-layer system of heterogeneous (by thermal-physical properties) layers the border lines of which move by time is based on the above presented material.

MM comprises the differential equation of thermal conductivity, establishing the connection between the temporal and spatial changes of temperature at any point of sample along the axis *X* under the condition of existing the inner source of heat q_V and moving border lines:

$$\frac{\partial E_i}{\partial \tau} = q_{v_i} + \frac{\partial^2 w_i}{\partial x_i^2} + v_i(\tau, x_i)\frac{\partial E_i}{\partial x_i}, \tag{18}$$

where $i = 1,2,3$ are the order numbers of layers of the system "suspension – coating – basis"; $v_i(\tau, x_i)$ is a velocity of border line movement, determined by formula (4a).

The values of volume density of internal energy E and potential of thermal conductivity w are expressed via the integral transformations of Goodman and Kirchhoff [5] within the considered interval of temperatures:

$$E(T) = \int_{T_1}^{T_2} C(T)dT + E_P(T_1, T_2); \tag{19}$$

$$W(T) = \int_{T_1}^{T_2} \lambda(T)dT, \tag{20}$$

where $E_p(T_1, T_2)$ is the sum of unit heats of phase transfers in the interval of temperatures $\Delta T = T_2 - T_1$.

Equation (18), taking into account (19) and (20) in the one-dimension assigning can be presented as follows:

$$\frac{dT_i}{d\tau} = \frac{q_{v_i}}{C_i(T_i)} + a_i\frac{d^2 T_i}{dx_i^2} + v_i(\tau, x_i)\frac{dT_i}{dx_i} - \left(\frac{dE_P}{d\tau}\right)\Big/ C_i(T_i). \tag{21}$$

The conditions of heat exchange on the border lines of the system (thermal border line conditions) in general case are proposed for generalising by dependence (similar to dependence in work [5]):

$$G_R(\tau, q_R, T_R)_i = \beta_{Ri}(\tau)[q_R(\tau) - \varphi'_R(\tau)]_i + \psi_{Ri}(\tau)[(T_R(\tau))^\gamma - \varphi''_R(\tau)]_i, \tag{22}$$

where β_{Ri}, φ_{Ri}, ψ_{Ri} are the specified functions of time (stages), different for different system layers.

Various ways of specifying the thermal border line conditions can be employed simultaneously on the border lines of different layers. So, for instance, at stage I, considered above, it is specified the border line condition of the third type (the condition of thermal conductivity at the medium according to the Newton-Richmann hypothesis with the specified thermal conductivity coefficient α) in the form

$\beta_{R1}(\tau)=0;\ \psi_{R1}(\tau)=\alpha_1(\tau);\ \gamma=1,$ and also the condition of the first type for the temperatures $T_R(\tau)=T_H=const$:

$$\varphi''_R(\tau)=T_0=\begin{cases}T_{b0} & if \quad \tau=0;\\ T_H & if \quad \tau=\tau_1.\end{cases} \tag{23}$$

From the suspension layer, as well as on the inner border lines, the different border line conditions of the second type (heat flow density $\varphi'_{R1}(\tau)$ according to Fourier) are specified:

$$\beta_{R1}(\tau)=1;\ q_R=0;\ \psi_R(\tau)=0;\ \varphi'_{R1}(\tau)=-\lambda_1(T)\,dT/dx\,. \tag{24}$$

At stage II as a result of heat emission in the border layer, the heat flow from the medium changes its direction and is determined according to the law of thermal radiation of Stefan-Boltzmann (in the form of BLC of the third type):

$$\beta_{R1}(\tau)=0;\ \psi_{R1}(\tau)=-\varepsilon_{cor}\cdot\sigma_0;\ \gamma=4;\ \varphi''_{R1}(\tau)=T_H{}^4,$$

where ε_{cor} is a reduced power of blackness; σ_0 = 5.67·10^{-8} Вт/(м^{2}K^4) is a coefficient of radiation of absolutely black body (Stefan-Boltzmann's constant).

Moreover, the border line condition of the first type is implemented:

$$T_0=T_{R1}(\tau)=\begin{cases}T_H & if \quad \tau=\tau_I\\ T_B & if \quad \tau=\tau_{II}\end{cases}. \tag{25}$$

Under this condition, the border line condition from the suspension layer (on the outer side) can be expressed as follows:

$$\beta_{R1}(\tau)=1;\ q_{R1}(\tau)=q_V;\ \ \varphi'_{R1}(\tau)=-\lambda_1(T)\,dT/dx;\ \ \ \psi_{R1}(\tau)=0. \tag{26}$$

The border line condition within the suspension layer from the coating side, as well as on the sides of coating and sample are as follows:

$$\beta_{R1}(\tau)=\beta_{R2}(\tau)=\beta_{R3}(\tau)=1.0;\ q_{Ri}(\tau)=0;\ \varphi'_{Ri}(\tau)=-\lambda_i(T)\,dT/dx;\ \psi_{Ri}(\tau)=0. \tag{27}$$

The peculiarity of stage II is the existence of phase transfers under condition $\tau>\tau_{MB}$. Moreover, the correction of values $\lambda_i(T)$ and $C_i(T)$ in the coating layer is necessary.

The inner heat emission ($q_R(\tau)=q_V=0$) finishes at stage III; all other objective laws stay unchanged, as well as, consequently, the border line conditions.

Stages IV and V are characterised by the internal heat flows only and approximately equal thermal equilibrium with the medium (see Fig. 2).

The general MM of one-dimensional thermal conductivity in the multi-layer system of heterogeneous layers, the border lines of which move in time (at stages II and III), has been composed on the basis of the above discussed facts. This model contains the total differential equations of thermal conductivity fixed for every layer of the system, according to equation (21); the conditions of heat contact of every pair of joined layers (equity of temperatures and thermal flows); the conditions of heat exchange on the outer border line of the system and conditions of temperatures distribution within the system before the beginning of every process stage – equation (22).

Due to the complexity of general process, there is no possibility to employ the standard programmes of calculating the task of unstable thermal conductivity, for example, by implementing the final elements method.

3. Conclusions

The general mathematical model of the heat processes of forming the aluminide coating of the gas turbine blades, aimed at choosing the optimal modes and controlling the properties of obtained protective layers has been developed; there also has been composed the mathematical model of one-dimensional thermal conductivity within the multi-layer system of heterogeneous layers of blade coating, the border lines of which move in time (at stages II and III); the model comprises the general differential equations

of thermal conductivity fixed for every layer of the system, the conditions of thermal contact for every pair of joined layers (equity of temperatures and thermal flows), and the conditions of heat exchange on the outer border surface of the system and conditions of temperatures distribution within the system before the beginning of every process stage.

The results of calculation on the basis of the considered MM are in setting the connection between the temperature of hydrogen combustion and properties (depth and structure) of coating according to the known values of medium temperature and total time of process, as well as optimisation of the depth of suspension layer and time of generating the required coating ($\tau_{\Sigma opt} = \tau_{I} + \tau_{II} + \tau_{III}$).

The proposed mathematical model provides the increase of adequacy of mathematical description of generalized thermal process of forming the coatings from suspensions by introducing the members taking into account additional physical and thermodynamic processes of forming the layer and heat emission in the generated coating at the expense of oxidation of hydrogen, emitted from the suspension deposition in the course of heating the samples.

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