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METHOD FOR ESTIMATION OF THE AVERAGE LOCAL WORKING TEMPERATURES AND THE RESIDUAL RESOURCE OF METAL COATINGS OF GAS-TURBINE BLADES

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A new method is proposed for estimation of the average local operating temperatures and the residual service life (resource) of protective MCrAlY metal coatings of gas-turbine blades after a certain time of operation on the basis of experimental data on the residual content of aluminum in the coating of a blade and/or the width of its first depletion zone. A physical and a mathematical model of the processes of oxidation and diffusion of aluminum in the coating–blade alloy system, accounting for the kinetics of formation of the diffusion zone, are presented. Results of calculation of the local working temperatures and the residual resource of the coating of a blade at local points along the outline of the blade cross section by the method proposed with the use of data on the width of the first depletion zone are given.

The blades of modern power gas-turbine plants (GTP) are protected against high-temperature oxidation by MCrAlY (Cr is chromium, Al is aluminum, Y is yttrium, and M is a metal, nickel Ni and/or cobalt Co as a rule) coatings. The main element preventing the oxidation of the coating of a blade and the blade itself is aluminum, the initial percentage of which in the blade coating comprises 6–12% and provides tens of thousands of hours of the service life (resource) of the coating at working temperatures of 900–1000^{o}C. In the process of scheduled outages of turbines for preventive inspection and repair, the state of the coatings of the turbine blades and the blades themselves is examined, which makes it possible to measure the residual content of aluminum or the width of the surface aluminum-depletion zone in the blade coatings. In this case, there arise important practical problems associated with estimation of the residual corrosion resource of the coating of a blade and the average working temperatures at local points of the coating and of the blade surface near the coating.

In [1], the authors of the present work proposed a model for analysis of the mass-transfer processes (diffusion and aluminum oxidation) occurring in the coating of a GTP blade and a computational-experimental technique for estimation of the resource of this coating on the basis of determination of model coefficients by the inverse-problem (IP) method with the use of experimental data on the distribution of the aluminum concentration in the blade coating. We take the word resource to mean the time for which the aluminum content in the coating of a blade decreases to a certain level (becomes lower than 3%).

It is known that the rate of the mass-transfer processes occurring in the coating of a blade depends substantially on its temperature; for example, the coefficient of aluminum diffusion in the blade coatings being considered can increase by an order of magnitude with increase in their temperature by 100^{o}C. Such a strong temperature dependence of the mass-transfer coefficient of the coating of a GTP blade can be used for estimating the average operating temperatures at local points of this coating by the results of measurements of the aluminum distribution at these points after a certain time of work of the coating with the blade. In this case, it is assumed that the coating–blade system being considered was investigated in advance; there is a model of the mass-transfer processes occurring in it, similar to the model described in [1]; and the temperature dependences of the coefficients of this model are known. The essence of the method proposed is to determine the temperature at which the calculated distribution of aluminum in the coating–blade system is close to the measured one. After the average local temperature of the coating of a blade is determined, its residual resource can be estimated by the method proposed in [1].

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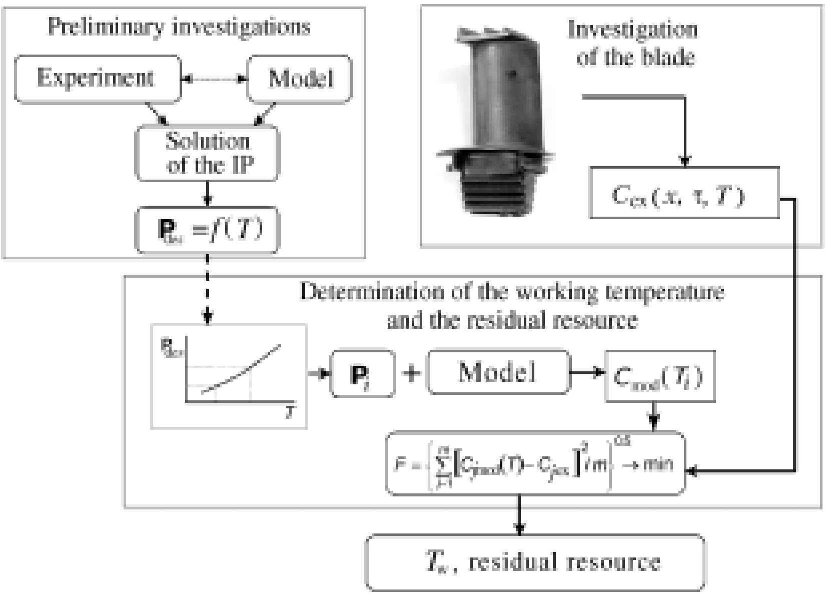

Fig. 1. Scheme of the method for estimation of the average working temperatures and the residual resource of the coating of a GTP blade.

At present, the local temperatures of the metal coatings of blades are sometimes estimated by the geometric sizes of the grains of the phases forming the microstructure of the alloy of the blades [2]. However, this method cannot accurately determine the temperature of the coating of a blade and cannot be used in a large number of cases because of the dissolution of the phases being analyzed.

The aim of the present work is to develop a method for estimation of the average working temperatures and the remaining resource of the MGrAlY coatings of GTP blades after a certain time of operation the basis of a model of diffusive dispersal of aluminum in these coating and experimental data on the residual content of aluminum in them.

We take the word "average working temperature" of the coating of a blade to mean the temperature at a local point of this coating, measured beginning with the activization of the diffusion processes (~850^{o}C for the system being considered) and ending the instant a maximum temperature of the coating is attained and averaged over the time of work of the coating.

Description of the Method. The method of determining the average working temperature and the remaining resource of the coating of a blade is based on the computational-experimental approach described in [1]. The essence of it is that the experimental data on a process and an object are used for identification of the parameters of a mathematical model by solving the inverse problem, which is then used for prediction of physical processes.

The scheme of estimation of the working temperatures and the residual resource of the coating of a GTP blade is presented in Fig. 1. The method proposed, as the method described in [1], is computational-experimental and is realized in the following three stages.

Preliminary investigations. Physical and mathematical models of the mass-transfer processes occurring in the coating–blade system are selected or constructed, the concentration of aluminum in this system at different temperatures and the time of its oxidation are measured, and the temperature dependences of the model parameters $\mathbf{P}_{des}$ are determined by the inverse-problem method described in detail in [1, 3].

Investigations of a blade. The state of the coatings of the blades of a GTP after a certain number of hours of their work is examined in the process of a scheduled outage of the GTP. This makes it possible to measure the residual content of aluminum in the coating of a blade or the width of the surface aluminum-depletion zone at different points having, as a rule, different temperatures. These data can be obtained by a destructive method (e.g., the method of x-ray spectroscopic microanalysis) or methods of nondestructive control.

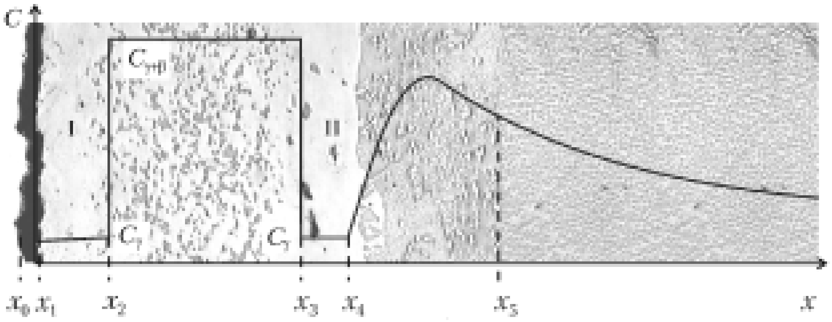

Fig. 2. Typical Al-concentration distribution in the coating and in the main alloy of a blade: zone $x_0 < x < x_1$ is an Al_2O_3 oxide; $x_1 < x < x_2$ is a depletion zone I where only the γ-phase exists; $x_2 < x < x_3$ is a two-phase $\gamma + \beta$-region (zone); $x_3 < x < x_4$ is a depletion zone II; $x_4 < x < x_5$ is a diffusion zone; $x_1 < x < x_4$ is a coating; $x > x_4$ is the main alloy. C, %; x, m.

Determination of the average working temperatures at local points of the coating of a blade and its residual resource. Calculations are carried out with the model used in the preliminary investigations. The inverse problem on the determination of the temperature T_i at a local point of the coating of a blade at which the Al-concentration distribution calculated at this point by the parameter $\mathbf{P}_{\text{des}}(T_i)$ and the model C_{mod}, is close to the experimental Al concentration distribution C_{ex} at the same point (the quantity F presented in Fig. 1 tends to a minimum). In such a way the temperatures at all the local points at which the residual Al content is known is determined. When the working temperatures at local points of the blade coating are determined, the residual resource of the coating can be easily estimated with the use of the same model and the resource criterion described above and in [1]. It should be noted that the residual resource of the blade coating at its local points can be calculated only when the average temperatures at these points are known because these temperatures determine the values of the model coefficients $\mathbf{P}_{\text{des}}(T)$ used for calculating this resource.

Approbation of the Method. Let us consider, in greater detail, the possibility of use of the method proposed for determining the average working temperatures and the residual resource of MGrAlY coatings of thickness 180–280 μm, applied to a cooled GTP blade. Preliminary experimental investigations of the coating–blade metal system have shown that at the interface between the coating and the blade there arises a diffusion zone in which Al is accumulated because of the reactive diffusion (Fig. 2). Therefore, below we consider a physical and a mathematical model accounting for the existence of such a zone.

Physical model. An oxide film is formed in the coating of a blade as a result of the combination of aluminum with oxygen absorbed from the gaseous medium and transferred, by diffusion through the oxide layer $x_1 - x_0$, to the oxide–coating interface x_1. Aluminum diffuses from the coating in two directions: 1) to the oxide–coating interface x_1, where it reacts with oxygen and 2) to the coating–main alloy interface x_4, where it is accumulated in the diffusion zone and then is transferred to the main alloy.

As a result of the diffusion of Al from the two-phase $\gamma + \beta$-zone to the coating, there arise a one-phase Al-deficient zones with a decreased Al content (γ phase) on both the oxide side (depletion zone I) and the main alloy side (depletion zone II). All Al leaves the two-phase $\gamma + \beta$-zone of the coating because of the disappearance (depletion) of the β-phase. The Al-concentration distribution in a MCrAlY coating has the form of a step curve; in the diffusion zone at the interface between the main alloy and the coating, this distribution has the form of a curve with the maximum value determined by the limiting content of Al (C_{max}) in the intermetal compounds formed in the diffusion zone.

The coating–main alloy system can be divided into six main zones: 1) the oxide zone $x_0 < x < x_1$; 2) the Al-deficient zone $x_1 < x < x_2$, where only the γ-phase exists; 3) the two-phase zone $x_2 < x < x_3$, where γ- and β-phases exist simultaneously; 4) the Al-deficient coating zone $x_3 < x < x_4$ with the γ-phase; 5) the diffusion zone in the main alloy $x_4 < x < x_5$, in which Al is accumulated; 6) the zone $x > x_5$ in the main alloy, into which Al is transferred from the diffusion zone. In the model developed by the authors earlier and described in [1], five zones (minus the diffusion zone) were considered, which takes place often in coating–main alloy systems.

Aluminum is accumulated in the diffusion zone with time because, in it, different intermetal compounds are formed due to the difference in quantitative composition and, accordingly, in thermodynamic equilibrium between the elements of the coating and the main alloy. Then, Al diffuses from the diffusion zone to the main alloy. In the above-described model, all boundaries other than the boundary x_4 (interface between the coating and the main alloy) are moving. The boundaries move to meet each other as a result of the increase in the content of the β-phase in the two-phase $\gamma + \beta$-zone from which Al diffuses. The total content C of Al and the β-phase C_β in the two-phase $\gamma + \beta$-zone $x_2 < x < x_3$ decreases with time.

Mathematical model. A mathematical model of the processes of oxidation and diffusion of Al, in which a diffusion zone is not considered, is described in detail in [1]. Below are only additions to this model, which allows one to take into account the existence of a diffusion zone in the system being considered. For this purpose, in accordance with the above-described physical model (Fig. 2), into the diffusion equation

$$\frac{\partial C}{\partial \tau} = \frac{\partial}{\partial x}\left[D_{\text{ef}}\frac{\partial C}{\partial x}\right] + W \tag{1}$$

we introduced the term W for the computational region $x_1 < x < x_\infty$. This term defines the rate of uniform accumulation (extraction) of Al in the diffusion zone of width $\Delta y = x_5 - x_4$ as a result of the formation of new phases. In this case, the Al flow passing from the coating to the diffusion zone can be defined as

$$J_{\text{m.a}}(x_4, \tau) = W(C, x, \tau)\,\Delta y(\tau)\,, \tag{2}$$

where the width of the diffusion zone Δy increases with time due to the movement of the boundary x_5 to the right and the growth of this zone. It is assumed that the law of this growth is similar to the law of growth of an oxide film and is defined by the parabolic function

$$\Delta y(\tau) = x_5(\tau) - x_4 = k_{\text{d.z}}\sqrt{\tau - \tau^0_{\text{d.z}}}\,. \tag{3}$$

The coefficient $k_{\text{d.z}}$ and the quantity $\tau^0_{\text{d.z}}$ in relation (3) are determined by experimental data on the increase in the thickness of the diffusion zone with time.

The values of W at nodes of a computational finite-difference grid differ from zero only in the diffusion zone $x_4 < x < x_5$ and depend on the difference between the concentrations $C_{\max} - C$ to the m power; this dependence is defined as

$$W = W(C, x, \tau) = \begin{cases} k_W (C_{\max} - C)^m\,, & x_4 < x < x_5\,; \\ 0\,, & x_1 < x < x_4\,,\ x > x_5\,, \end{cases} \tag{4}$$

where k_W is the coefficient of the rate of accumulation of Al in the diffusion zone.

The diffusion coefficient D_{ef}, the coefficient k_W, and the exponent m in the mathematical model (1)–(4) are determined on the basis of experimental data in the process of solution of the inverse problem. As such data, the Al-concentration distributions in the coating and in the main alloy, the width of the first depletion zone, the width of the oxide film, and the width of the diffusion zone at different instants of time can be used.

The diffusion coefficient D_{ef} in (1) has a finite value everywhere over the computational region, excepting the subregion $x_2 < x < x_3$, where it is assumed to be equal to an infinitely large value because of the absence of the Al-concentration space gradient.

In the above-described model and in the model presented in [1], the following assumptions are used: a) the main physicochemical processes in the coating and in the main alloy of a blade do not change in character with time; b) only one element (Al) participates in the formation of the oxide film (for the coatings being considered this assumption was supported by numerous experiments of duration 20,000 h; c) an oxide is formed only at the boundary x_1; d) the thermodynamic features of the phases and the intermetallic compounds in the coating and in the main alloy are not considered; e) spalling of the oxide film is absent; f) the diffusion coefficient D_{ef} determined in the process of solution of the inverse problem is an effective characteristic independent of time.

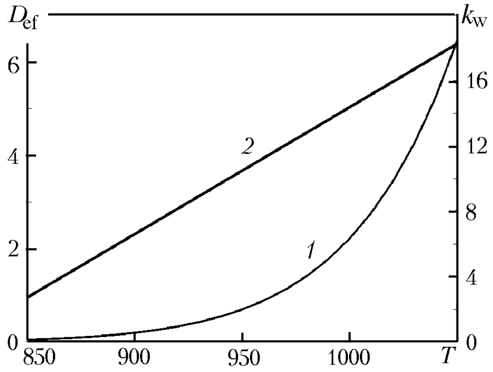

Fig. 3. Dependence of the effective diffusion coefficient $D_{ef}\cdot 10^{15}$ (1) and the Al-accumulation rate coefficient $k_W\cdot 10^8$ in the diffusion zone (2) on the temperature T. D_{ef}, m^2/sec; T, $^\circ$C.

Experimental. The coefficients D_{ef}, k_W, and m in the mathematical model (1)–(4) were determined in the process of solving the inverse problem with the use of experimental data obtained at the I. I. Polzunov Central Boiler-Turbine Institute (St. Petersburg). Samples with NiCoCrAlY coatings with an initial Al content of 8.4% were held in electric furnaces at 900, 950, and 1000°C as long as 20,000 h in an air medium. A coating was applied to nickel (IN-738LC) alloys with the use of the LPPS vacuum-plasma technology. The metallographic examination of the structure of these samples in the initial state and after a thermal treatment during 300, 700, 1000, 5000, 10,000, and 20,000 h was carried out with the use of a microscope, which made it possible to construct curves of change in the Al concentration across the thickness of the coating.

As a result of the solution of the inverse problem with the use of these experimental data, we determined the temperature dependences of the coefficients D_{ef} and k_W, presented in Fig. 3. It was established that this dependence for D_{ef} is defined by the Arrhenius law, and, for k_W, represents a linear dependence. The method of solving the inverse problem was described in detail in [3]. The exponent m, determined also from the solution of the inverse problem, was independent of the temperature, and equal to 0.65. The value of C_{max} corresponded to the initial content of aluminum in the coating, equal to 8.4%. The strong temperature dependence of the coefficients D_{ef} and k_W allows them to be used for estimating the average working temperatures of the protective coatings of GTP blades by the above-described method.

To elucidate the possibility of estimating the average working temperature of a blade coating with the method proposed and the stability of solution of the inverse problem, we solved a number of test problems by the following scheme:

1) a numerical experiment is carried out, the direct problem on mass transfer with predetermined parameters is solved; a computational experiment is conducted for the purpose of determining the width $\delta = x_2 - x_1$ of the first depletion zone $x_1 < x < x_2$ (Fig. 2);

2) the inverse problem on the value of the depletion zone is solved using exact data and the temperature determined is compared with the initial temperature;

3) the inverse problem on the value of the depletion zone is solved using disturbed data and the temperature determined is compared with the initial temperature.

The computational experiment was carried out at the following model parameters: the thickness of the coating of a blade was 200 μm, the time of the process was 20,000 h, the temperature was 900°C, the diffusion coefficient was $D_{ef} = 2\cdot 10^{-16}$ m^2/sec, the rate of Al accumulation was $k_W = 9.6\cdot 10^{-8}$, and the exact width of the depletion zone was $\delta_{ex} = 23.447$ μm.

The results of the test problems solved are presented below. As a criterion of solution of the inverse problem, we used a minimum deviation of the calculated width δ_{mod} of the first depletion zone from the experimental one δ_{ex}

$$F = \delta_{mod} - \delta_{ex} .$$

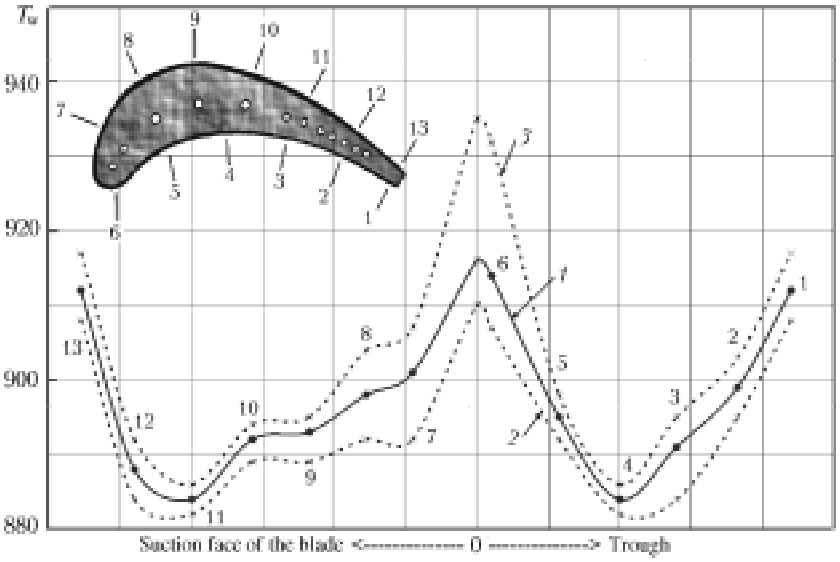

Fig. 4. Distribution of the average working temperatures T_w over the outline of the cross section of a blade (the points on the graph correspond to the numbered points of the blade cross section). Calculation for the medium (1), minimum (2), and maximum (3) thicknesses of the depletion zone. T_w, °C.

The temperature T determined from the solution of the inverse problem with the use of an exact value of the width of the first depletion zone δ_{ex} was equal to 900.006°C and the criterion F corresponding to it was equal to 0.005. The temperature T determined from the solution of the inverse problem with the use of an inexact value of the width of the depletion zone $\delta_{ex} = 27.28$ (the error was +10%) was equal to $T = 902.7$°C and the corresponding criterion was equal to $F = 0.007$; it was found that, at $\delta_{ex} = 21.08$ (at an error of −10%), $T = 897.17$°C and $F = 0.02$.

Thus, when the width of the depletion zone of the coating of a GTP blade is determined with an error of ±10%, the error in determining the temperature of the coating does not exceed ±3.0°C, which accounts for ±0.34% of the temperature 900°C and points to the high degree of stability of the inverse problem in determining the temperature.

Using the computational-experiment data, we also analyzed the influence of the error in measuring the width of the depletion zone of the coating of a GTP blade on the accuracy of calculating its residual resource. When the error in measuring this quantity was +10 and −10%, the error in determining the remaining residual of the coating at a temperature of 900°C was +6.1 and −7.1% respectively.

The solution of the above-indicated test problems has shown that the inverse problem being considered is stable and allows one to estimate the temperature and the residual resource of the coating of a GTP blade by the width of its first depletion zone. In this case, the errors are commensurable with the errors (do not exceed them, in the test problems) in measuring the width of the first depletion zone. It should be noted that the measurement of the Al-concentration distributions in the coating of a blade and in its main alloy is a more laborious procedure that is conducted with the use of more complex methods destructing the blade and the coating, whereas the width of the first depletion zone can be measured with nondestruction-control devices. Therefore, determination of the temperature and the residual resource of the coating of a blade on the basis of experimental data on the width of its first depletion zone is of great practical importance.

Below are the results of testing of the method proposed for calculating the local working temperatures and the residual resource of the coating of an actual GTP blade along the outline of the blade cross section by the data on the width of the first depletion zone of the coating. We considered an NiCoCrAlY coating with an initial Al content of 8.4%, applied to a blade of a GTP, which was used in the GTP for 26,400 h. This coating was experimentally investigated in advance at points indicated in Fig. 4. On the basis of the results of these investigations we determined the position of the boundary of the oxide film x_1 and the right boundary of the depletion

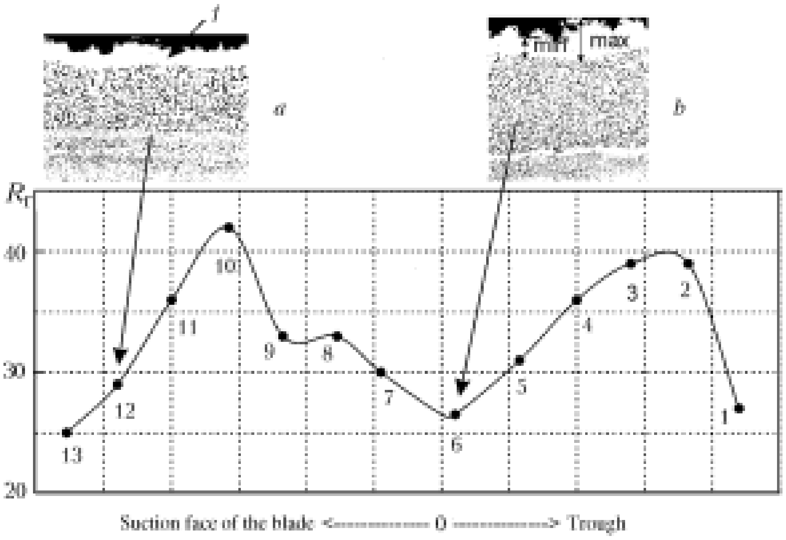

Fig. 5. Distribution of the residual resource R_r of the coating of a blade along the outline of its cross section and examples of microstructures of the coating: a) section No. 12 (Fig. 4); b) section No. 6; 1) depletion zone I. R_r, ths. h.

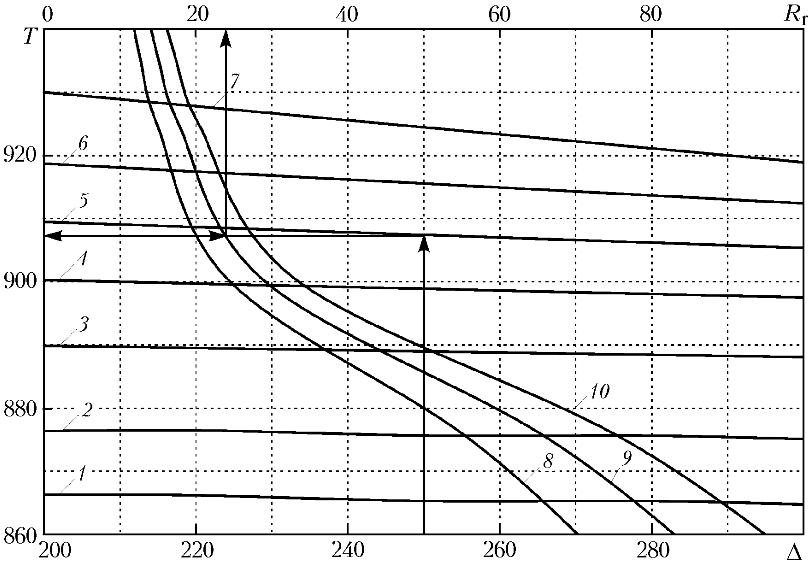

Fig. 6. Nomogram for estimation of the average working temperatures and the residual resource of the coating of a blade for an operating time of 26,400 h. T, °C; Δ, μm; R_r, ths. h.

zone x_2. These data were used for determining the local working temperatures and the remaining resource of the coating along the outline of the blade.

Figure 4 shows the local working temperatures along the outline of the blade, determined by the average thickness of the depletion zone, as well as curves of minimum and maximum temperatures corresponding to the maximum and minimum thicknesses of the depletion zone determined by the photographs of the microstructures of metallographic sections (Fig. 5) of local sites of the blade. The positions of the oxide-film boundary x_1 and the right boundary of the depletion zone x_2, which determine the width of the first depletion zone, are shown in Fig. 5. This figure also shown the results of determination of the residual resource of the blade coating. It is seen that it varies from 25,000 to 42,000 h depending on the temperature and the thickness of the coating along the outline of the blade.

The thickness of the coating being investigated varied from 200 to 280 μm. The maximum difference between the average and maximum thicknesses of the depletion zone, caused by a temperature difference of 19°C, reached 70% at the input edge of the blade.

Figure 6 shows a nomogram obtained after 26,400 h of work of a blade. If the thickness of the coating of the blade and its first depletion zone are known, by this nomogram one can easily determine the working temperature of the coating and estimate its resource. Curves 1–7 are dependences of the temperature of the blade coating T on its thickness Δ, constructed for the depletion-zone thicknesses 5, 10, 20, 30, 40, 50, and 60 μm. Curves 8–10 are dependences of the resource R of the blade coating on its temperature, constructed for the coating thicknesses 200, 250, and 300 μm. Such a nomogram allows one to rapidly estimate both the average working temperature and the residual resource of the coating of a GTP blade at its different sites.

CONCLUSIONS

1. A new method has been developed for estimation of the average working temperature and the residual resource of the protective metal coatings of GTP blades on the basis of experimental data on the residual content of aluminum in the coating of a blade and/or the width of its first depletion zone, measured by nondestructive-control devices.

2. An improved mathematical model based on the diffusion equation, which accounts for the kinetics of formation of the diffusion zone in the coating–blade alloy system, has been proposed.

3. With the use of the method and model developed, the average working temperatures of the NiCoCrAlY coating with an initial Al content of 8.4% of a GTP blade operating for 26,400 h were estimated at 13 points along the outline of the cross section of the blade.

NOTATION

C, weight concentration, %; D, diffusion coefficient, m^2/sec; F, functional of the discrepancy between the measured and calculated values; J, density of a flow of a material (aluminum), m/sec; k_W, coefficient of intensity of accumulation of Al in the diffusion zone; $k_{\text{d.z}}$, coefficient in the law of increase in the width of the diffusion zone; m, total number of space-time measurement points, exponent; $\mathbf{P}$, vector of model parameters; R, resource, residual resource, h; T, temperature, °C; W, source of Al in the diffusion zone, 1/sec; x, coordinate, m; β, phase; γ, phase; δ, width of the first depletion zone, μm; Δ, thickness of the coating, μm; Δy, width of the diffusion zone, m; τ, time, sec. Subscripts: 0, initial, known from the literature; 1, 2, 3, 4, 5, numbers of the boundaries of different zones in the physical model; d.z, diffusion zone; mod, model; m.a, main alloy; r, residual; w, working; ex, experimental; des, desired, determined from the solution of the inverse problem; ef, effective; j, number of a point at which the Al concentration is measured, $j = 1 \ldots \text{m}$; i, number of an iteration; min, minimum; max, maximum.

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