NEW METHOD OF COATED GAS TURBINE BLADES REMAINING LIFE TIME DETERMINATION

L.B. Getsov, N.V. Mozaiskaja, A.I. Rybnikov
ITTPh NAN, Ukraina

P.G. Krukovski, K.A.Tadlja
NPO ZKTI, Ukraina

Main theses

In the course of exploitation of gas-turbine units (GTE) their turbine blades accumulate defects. These defects are caused both by the static stress caused by centrifugal forces and by the thermo-cyclic stress. Since gas turbines usually operate under variable conditions, the time of exploitation cannot be taken as a reliable parameter for determination of the remaining life time. Unfortunately in many cases, at the moment when a GTE is stopped for maintenance the thermal conditions of previous exploitation of the blades are unknown.

In this presentation a new method of remaining life time determination for coated blades is considered. The long-term strength decay evaluation is carried out on the basis of the equivalent exploitation temperature – T_{eq}, the known exploitation time – τ and the static stresses – σ.

Four different cases can be considered:

1. Uncooled blades, working in constant conditions (at constant temperature). Blades of this type (type 1) in stationary mode of operation have constant temperature and constant stress in each cross section;
2. Cooled blades in stationary mode of operation (at constant gas temperature). In this case blades have some distribution of stresses and temperatures in each cross section. For calculation of the remaining life time of these blades (type 2) the thermostatic stress is usually omitted and only the static centrifuge stress is used;
3. Uncooled blades in variable mode of operation (type 3) – for each mode of operation in each cross-section they have constant temperature and stress;
4. Cooled blades working under variable conditions (type 4).

In the recent works [1-6] the surface-layer processes in the blades were investigated as a function of the long expositions to the high temperature. By means of solving the direct and inverse diffusion problem, the authors have developed some models and methods of prediction for these processes. On the basis of these results the temperature distribution in the surface layer for the weak cross section can be found out by using the X-ray analysis and the quantitative metallographic analysis of the blade, taken out from the engine. These calculations are based on the temperature dependences of the coating elements diffusion characteristics. This way, for example, an evaluation of the average operating temperatures of the coating, type NiCoCrAlY with initial concentration of the Al=8.4%, was performed [6] – Fig.1 (cooled blades, IN738 alloy; worked for 26400 hrs. in the turbine).

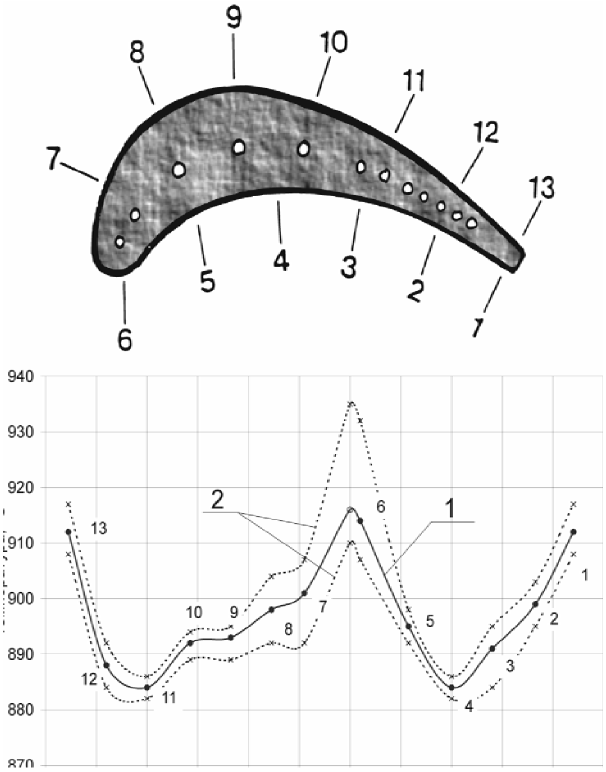

Fig. 1. Work temperature (^oC) distribution around the cross section contour after exploitation for 26,400 hrs. Numbered points on the plot correspond to the numbered positions on the blade. Curve 1 – calculated; curves 2 – error range of the measurements]

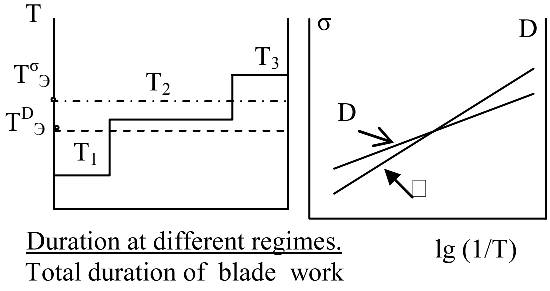

Fig. 2. The diagram of change of temperature during operation (a) and temperature dependences of long durability and factors of diffusion (b)

Determination of T_{eq}^{σ}

Due to the differences in the temperature dependence for diffusion coefficients and long-term strength, temperature value T_{eq}^{D} (obtained from the surface-layer elements redistribution) can be used for remaining life time determination only in case of the Type-1 blades. In all other cases the comparison of T_{eq}^{σ} and T_{eq}^{D} is required (see Fig. 2).

The method, described below, is based on the following assumptions:

1. The remaining life time of the blade is determined by the remaining life time of its bulk metal;
2. The temperature of the blade cross section is supposed to be constant and it corresponds to the maximum temperature value in the maximally loaded cross section;
3. The damages for different temperatures and different stresses are summed according to the linear law and at the moment of destruction the following relationship is true:

$$\Sigma(\tau_i / t_i)=1 \qquad (1),$$

where τ_i is exploitation time at the temperature T_i and under the stress σ_i; t_i is the time of destruction under the same conditions. It is necessary to mention, that for traditional estimation, it is more appropriate is to use "0.87" instead of "1" in the right part of the Eq.1.

Let us suppose that we have the following distribution of work-times for a gas turbine unit: $\tau_1 : \tau_2 : \tau_3 : \tau_4 : \tau_5$ … under different conditions with the corresponding power N_1 , N_2 , N_3 , N_4 , N_5 … and according to blades temperatures T_1, T_2, T_3, T_4, T_5 … In this case the time of exploitation can be found as $\tau = \mathbf{a}\, \Sigma\tau_i$.

Let's use the Larson-Miller dependence:

$$P(\sigma) = T(C+\lg t), \qquad (2)$$

where t is the time of destruction at the temperature T and stress σ. The value of the parameter C (in the first approximation C=20) can be specified for the involved temperature interval from the experimental long-term strength of the blade material.

Using (2):

$$t_1=10^{[P(\sigma_1)/T_1]-C};\ t_2=10^{[P(\sigma_2)/T_2]-C};\ t_3=10^{[P(\sigma_3)/T_3]-C};\ t_4=10^{[P(\sigma_4)/T_4]-C};\ t_5=10^{[P(\sigma_5)/T_5]-C}\ \ldots \qquad (3),$$

where σ_i is determined by the rotation frequency in the regime N_i, $P(\sigma_i)$ and C can be obtained from the reference data for the corresponding material.

Taking into account that the damage summation is linear (1) and the relationship (3), we can determine the value **a**. It corresponds to the given time distribution for different operation regimes $\tau_1 : \tau_2 : \tau_3 : \tau_4 : \tau_5\ldots$

Value of the equivalent temperature T_{eq} can be obtained from the dependences:

$$T_{eq}^{\sigma}=\frac{2{,}3P(\sigma_{eq})}{\ln\left(\sum\tau_i \Big/ \sum\tau_i\exp(-2{,}3P(\sigma_{eq})/T_i)\right)};$$

$$P(\sigma_{eq})=T_{eq}^{\sigma}\,(C+\lg\tau_{p\,eq});$$

$$\sum\frac{\tau_i T_i}{P(\sigma_i)-CT_i}=1, \qquad (4)$$

which parameters are values of operating time $\tau_1 : \tau_2 : \tau_3 : \tau_4 : \tau_5\ldots$ on the various power setting characterized by values T_i and σ_i.. Here P (σ_{eq}) – parameter of dependence of Larson-Miller. Thus, the remaining life time of the blades 2-4 after the turbine operation during the time $\boldsymbol{\tau}$ can be determined for the stress $\boldsymbol{\sigma_{eq}}$ multiplied by the long-term strength coefficient (obtained from the initial turbine project or taken from the strength standards) as the destruction time at the temperature $\mathbf{T_{eq}^{\sigma}}$ minus the turbine operating time.

If we suppose that the exploitation temperatures changed according to the requirements specification (or according to the recorded exploitation parameters), then it is possible, as it is described above, to determine the remaining life time. Thus the calculated $\mathbf{T_{eq}^{\sigma}}$ is based on the time ratio $\tau_1 : \tau_2 : \tau_3 : \tau_4 : \tau_5\ldots$, but in most cases this ratio is unknown. For determination of the real (objective) ratio $\tau_1 : \tau_2 : \tau_3 : \tau_4 : \tau_5\ldots$ the calculated $\mathbf{T_{eq}^{D}}$ can be used.

Method of working time ratio determination for different regimes

By solving the inverse diffusion problem for the experimental Al distribution in the surface layer, the value of the diffusion coefficient can be determined (for the real temperature change law during the turbine exploitation). Then, if the diffusion temperature dependence is known for the selected element, the value of $\mathbf{T_{eq}^{D}}$ can be determined. This temperature ($\mathbf{T_{eq}^{D}}$) will be equivalent to the average temperature determined using Al diffusion parameters. It can be used as an equivalent temperature for determination of the residual corrosion life time of the coating. But for the determination of the blade remaining life time under applied stress (centrifugal bending stress, or especially thermocyclic stress) this temperature ($\mathbf{T_{eq}^{D}}$) must be corrected according to the aforesaid statements.

Let us suppose, that the element distribution in the diffusion layer does not depend on the consecution of the temperature-time conditions of the process. Then, by solving the direct diffusion problem step by step (for different initial conditions) at different temperatures $\mathbf{T_i}$ and times of exploitation $\boldsymbol{\tau_i}$, the distributions of Al and oxide layer thickness can be obtained (corresponding to the exploitation times). By comparing this data with the calculated $\mathbf{T_{eq}^{D}}$ for the different points of the profile (Fig. 1), the ratio of times $\tau_1 : \tau_2 : \tau_3 : \tau_4 : \tau_5\ldots$ can be obtained.

Method of T_{eq}^{D} determination

Let us consider the processes in the solid coating **MeCrAlY** (Fig. 3).

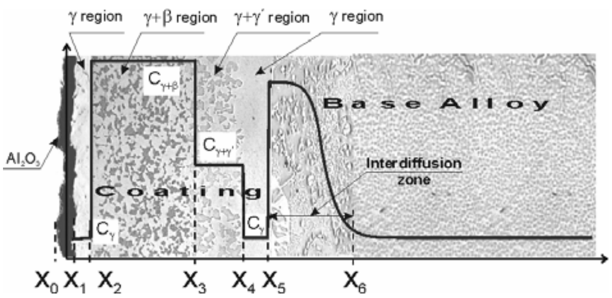

Fig. 3. Typical Al concentration distribution in the coating layer and the bulk alloy

The oxide **Al_2O_3** is formed during the blade exploitation by the combination of **Al** and oxygen, absorbed from the gas environment and diffused trough the oxide layer (**x_1-x_0**) to the oxide-coating interface marked as **x_1**. Diffusion of **Al** from the coating occurs in two directions: – to the oxide-coating interface **x_1**, where it reacts with the diffused oxygen; -- to the coating-bulk alloy interface **x_4**, where it is accumulated in the inter-diffusion zone and then, depending on the Al concentration in the bulk metal, diffuses either to the bulk alloy or to the coating.

Due to the Al diffusion from γ+β two-phase coating region, depleted **Al** single-phase zones with reduced concentration of Al (γ-phase) are formed on both sides of the coating – on the side of the oxide and on the side of the bulk alloy (depleted zones I and II, Fig. 2). All **Al**, diffused from the coating, is diffused from the γ+β two-phase coating region due to the disappearance (consumption) of the β-phase. **Al** concentration curve in the MCrAlY coating has the shape of a stepped line, and in the bulk alloy region – curve with the maximum in the inter-diffusion zone.

The process of the Al mass-exchange within the calculation region $x_1 < x < x_\infty$ can be described with the following diffusion equation:

$$\frac{\partial C}{\partial \tau} = \frac{\partial}{\partial x}\left[D_{eff}\frac{\partial C}{\partial x}\right] + W, \qquad (5)$$

$$\tau > 0, \quad x_1 < x < x_\infty, \; C = C(x,\tau),$$
$$W = W(x,\tau), \; D_{eff} = D_{eff}(x),$$

$$x_1 = x_1(\tau), \; x_2 = x_2(\tau),$$
$$x_3 = x_3(\tau), \; x_5 = x_5(\tau),$$

with the initial condition:

$$C(x,0) = C(x) = \begin{cases} C_n^0 & 0 < x < x_4 \\ C_{oc}^0 & x \ge x_4 \end{cases}, \qquad (6)$$

the boundary condition for the infinity:

$$\frac{\partial C(x_\infty,\tau)}{\partial x} = 0 \qquad (7)$$

and the boundary condition on the moving interface x1, describing diffusion flux (due to the concentration gradient) of **Al** from the coating to the left (Fig. 3), forming the oxide:

$$J_{\text{ок}}(x_{1+},\tau) = -D_{eff}\frac{\partial C(x_1,\tau)}{\partial x}. \qquad (8)$$

The flux (8) conjointly with the flux $C(x_1,\tau)\frac{dx_1}{d\tau}$ (formed by the moving the interface **x_1** to the right) produce the total **Al** flux, which creates oxide film with the thickness of **Δx**. Kinetics of the oxide film growth can be described with two parabolic equations:

$$\Delta x(\tau) = x_1(\tau) - x_0(\tau) = \\ = \begin{cases} k_{\text{ок}}^{*}\cdot\tau^{0.5}, \; 0 < \tau < \tau^{*} \\ k_{\text{ок}}^{**}\cdot\sqrt{\tau-\tau^{0}}, \; \tau^{*} < \tau < \infty \end{cases}, \qquad (9,10)$$

where k_{ox}^*, k_{ox}^{**} – are the coefficients of the oxide film growth intensity (so-called constants of oxidation), τ^* – boundary time point, before it the kinetics obey the oxidation law (9), after – the oxidation law (10). The curves (9) and (10) intersect at the time point τ^*; τ^0 – time point (negative value) of intersection for the curve (10) and the time axis τ. The necessity of using two parabolic laws (9) and (10) for description of the Al-oxide growth can be explained by faster formation (growth) of the θ-oxide phase before the time point τ^*, and by slower growth of the Al_2O_3 α-oxide phase for $\tau > \tau^*$. The coefficients $k^*_{ок}$, $k^{**}_{ок}$, τ^0 and the value τ^* in (9) and (10) are determined from experimental data of the oxide growth as a function of time.

The following concentration conditions are taken for the moving boundaries x_2 and x_3:

$$C(x_{2-},\tau) = C(x_{3+},\tau) = C_\gamma,$$
$$C(x_{2+},\tau) = C(x_{3-},\tau) = C_{\gamma+\beta}. \quad (11)$$

Thus, by analogy with the boundary condition (8) for the fixed boundary x_4 the diffusion flux of the Al from the coating to the left (which forms the diffusion zone $\Delta y = x_5 - x_4$) and diffusion of Al to the bulk alloy can be written as:

$$J_{oc}(x_{4-},\tau) = -D_{эф}\frac{\partial C(x_{4-},\tau)}{\partial x}. \quad (12)$$

According to the physical model (Fig. 3), the flux of Al (12) from the coating induces a new phase formation in the diffusion zone having the thickness $\Delta y = x_5 - x_4$, i.e.:

$$J_{oc}(x_{4-},\tau) = W(x,\tau)\cdot\Delta y(\tau), \quad (13)$$

where W is Al mass, which diffused from the coating to the diffusion zone $x_4 < x < x_5$ depending on $C_{\gamma+\beta} - C_\gamma$ and determined by the relationship

$$\Delta y(\tau) = x_5(\tau) - x_4 = k_D\cdot\sqrt{\tau - \tau_D^0}. \quad (14)$$

The coefficient k_D and the value τ_D^0 in (14) are determined from the experimental data of the diffusion zone increase with time. $\Delta y = x_5 - x_4$ – diffusion zone width, which increases with time due to boundary x_5 shift to the right according to the parabolic law:

$$W = W(x,\tau) = \\ = \begin{cases} k_w\cdot(C_{\gamma+\beta} - C_\gamma)^m, & x_4 < x < x_5 \\ 0, & x_1 < x < x_4,\ x > x_5 \end{cases}, \quad (15)$$

where k_w is the coefficient of Al precipitation in the diffusion zone.

Since in the system the coating/oxide film/bulk alloy mass balance should be fulfilled, according to (8) and (12) the total flux of Al from the two-phase coating will take the form:

$$J_\Sigma(\tau) = J_{ок}(x_{1+},\tau) + J_{oc}(x_{4-},\tau). \quad (16)$$

According to the physical model, all Al outgoing from the coating, actually outgo from the γ+β-two-phase coating zone by consuming the β-phase. Then the movement of the boundaries x_2 and x_3, and Al concentration decrease in γ+β- two-phase zone can be described by equation of the mass balance between Al diffusion fluxes through this boundaries and for diffusion fluxes due to the Al concentration differences in γ+β- and γ- phases ($\Delta C = C_{\gamma+\beta} - C_\gamma$):

$$J_\Sigma = J_\gamma(x_{2-},\tau) + J_\gamma(x_{3+},\tau) = \\ = \Delta C\cdot\frac{dx_2}{d\tau} + \Delta C\cdot\frac{dx_3}{d\tau} + (x_3 - x_2)\frac{dC_{\gamma+\beta}}{d\tau}, \quad (17)$$

where $J_\gamma(x_{2-},\tau) = -D_{eff}\dfrac{dC(x_{2-},\tau)}{dx}$ and $J_\gamma(x_{3+},\tau) = -D_{eff}\dfrac{dC(x_{3+},\tau)}{dx}$ are the diffusion fluxes towards the oxide and bulk alloy due to the Al concentration gradients to the left and to the right of the boundaries x_2 and x_3 correspondingly.

Expression (17) after dividing by J_Σ takes the form:

$$1 = \Delta C \cdot \frac{dx_2}{d\tau} / J_\Sigma + \Delta C \cdot \frac{dx_3}{d\tau} / J_\Sigma + \\ + \left(x_3 - x_2\right) \frac{dC_{\gamma+\beta}}{d\tau} / J_\Sigma = g_2 + g_3 + g_{2,3} \quad , (18)$$

where g_2 and g_3 are the portions of the total Al mass, whhic left the coating due to the boundaries x_2 and x_3 shifting correspondingly; $g_{2,3} = (1 - g_2 - g_3)$ – portion of the total Al mass, which left the coating due to the decrease of the Al β-phase concentration in the region $x_2 < x < x_3$. The values g_2 and g_3 directly affect the speed of shifting of the borders x_2 and x_3 and are taken as functions of concentration differences $\Delta C = C_{\gamma+\beta} - C_\gamma$:

$$g_2 = k_2 \cdot \frac{\Delta C}{C_n^0}, \; g_3 = k_3 \cdot \frac{\Delta C}{C_n^0}. \qquad (19)$$

From the equations (15) and (16) it is possible to obtain the laws of borders x_2 and x_3 shifting and the law of decrease of concentration of Al $C_{\gamma+\beta}$ in the two-phase zone:

$$\frac{dx_2}{d\tau} = J_\Sigma \frac{k_2}{C_n^0}, \; \frac{dx_3}{d\tau} = J_\Sigma \frac{k_3}{C_n^0}, \\ \frac{dC_{\gamma+\beta}}{d\tau} = J_\Sigma \left(x_3 - x_2\right)\left(1 - g_2 - g_3\right). (20)$$

the constants k_2 and k_3 in (19) can be obtained from the equation (20) using the experimental data of the borders x_2 and x_3 shifting dynamics and of the $C_{\gamma+\beta}$ plateau value in the region $x_2 < x < x_3$ for different time of tests or exploitation.

The total concentration of Al $C_{\gamma+\beta}$ depends on the β-phase concentration $C_\beta(\tau)$ in the coating as:

$$C_{\gamma+\beta}(\tau) = \\ = C_\beta(\tau) \cdot C_\beta^{Al} + \left[1 - C_\beta(\tau)\right] \cdot C_\gamma, \qquad (21)$$

where $C_\beta^{Al} = const$ – concentration of Al in the β-phase.

The diffusion coefficient D_{eff}, coefficient k_w and the power m in the mathematical model (5)-(21) can be obtained from the experimental data by means of the inverse problem solution.

The diffusion coefficient D_{eff} in (5) is correct for the whole solution region, excluding sub-region $x_2 < x < x_3$, where it was taken as a grater value due to the absence of the Al concentration space gradient.

$$J_{мд}(x_{4+}, \tau) = -D_{eff} \frac{\partial C(x_{4+}, \tau)}{\partial x}$$

returns back into the intra-diffusion zone and is added to the main flux (13).

The program complex COLTAN created in the ITTPh NAN Ukraina allows to calculate the Al concentration distribution in the coating and in the base blade material, T_{eq}^D and time ratios $\tau_1 : \tau_2 : \tau_3 : \tau_4 : \tau_5$…. in cooled blades for different operation modes. In case of uncooled blades (type 3) in order to obtain the time ratios the inverse problem must be solved for the blades taken from the GTE for different times of operation.

$$\tau_1 : \tau_2 : \tau_3 : \tau_4 : \tau_5 \ldots$$

Algorithm for calculation of residual life time

On the basis of the aforesaid the following several steps are used for determination of residual life of the coated blade removed from the turbine that has been running for the operation time τ:

1) determination of parameters of diffusion for the blade coating by means of experiments and calculations,
2) experimental determination of distribution of aluminium in different points of the surface layer of the coated blade taken out from the turbine,

3) calculation of the equivalent temperature T_{eq}^D according to a special method based on the solution of the reverse diffusion problem for experimental data on distribution of aluminium (see step 2),
4) calculation of allocation of the time of GTE operation in different modes $\tau_1 : \tau_2 : \tau_3 : \tau_4 : \tau_5 .... = r_1 : r_2 : r_3 : r_4 : r_5 ...$, corresponding to the power values N_1, N_2, N_3, N_4, $N_5 ....$ (operation time $\tau = \mathbf{a}\ \Sigma r_i$, a $\tau_i = ar_i$. according to the data obtained at the step 2,

   Al accumulated in the diffusion zone partially diffuses back into the coating, due to the gradient in concentration to the right of the border x_4. The related diffusion flux:
5) calculation of equivalent temperature T_{eq}^{σ} using the equation (4)
6) calculation of residual life of the set of blades (after operation during the time **τ**).

The algorithm of solution of the problem mentioned in the step 4 consists of a number of successive calculations of the direct diffusion problem (with different initial conditions) for different temperatures T_i (within the real range for the examined GTE) and operation times τ_i (in different modes) as a result of which we obtain the relevant distributions of aluminium and width of the oxide layer, corresponding to the operation times. Having these set of points for different conditions we chose those, in which:

- calculated Al distribution coincides with its experimental distribution,
- equivalent temperature coincides with $\mathbf{T_{eq}^D}$

Accord between these data and those obtained with the help of calculations for definition T_{eq}^D in different points of the blade profile allows to calculate the ratio of times $\tau_1 : \tau_2 : \tau_3 : \tau_4 : \tau_5 ....$ (see Fig.1, included as an example of solution of the problem of finding T_{eq}^D distributions) allows to calculate the ratio of times $\tau_1 : \tau_2 : \tau_3 : \tau_4 : \tau_5 ....$

In other words,

1. Knowing T_{eq}^D and the total operation time of the examined blade, we are able to write the following equation representing the sum of solutions of reverse problems for different operations modes contributing to the resulting distribution curve

$$F_1(\tau, T_{eq}^D) = \sum F_1(\tau_i, T_i^D) \qquad (22)$$

2. Knowing T_{eq}^D, we obtain a number of possible values τ_i-T_i^D from the equation (22)
3. Knowing different values T_{eqj}^D for different blade points we find the true values τ_I-T_i^D from the equation (22)
4. Having found the true values τ_i -T_i^D (step 3), we determine the value T_{eq}^{σ} using the formula (4)

The residual life of the set of blades (after the operating time **τ)** is calculated as the time value before fracture at temperature T_{eq}^{σ} under the stress σ_{eq}, multiplied by the strength safety factor (obtained in the course of strength calculations for blades on the design stage or by the safety factor chosen from the strength standards) minus the elapsed operating time τ.

As a basis for the above-mentioned calculations for MeCrAlY coatings the experimental data obtained in the present work can be used, namely:

- determination of Al concentration distribution on the basis of the coating layer thickness using the X-ray micro analysis method;
- determination of the volumetric share of the β-phase on the basis of coating layer thickness using digital optical metallography (for example, with the help of software made by "IstaVideoTest");
- measurement of the oxide film thickness on the coating surface and thicknesses of inner and outer de-alloyed layers.

These experimental data must be obtained for not less than three temperatures from the real GTE temperature range and for several

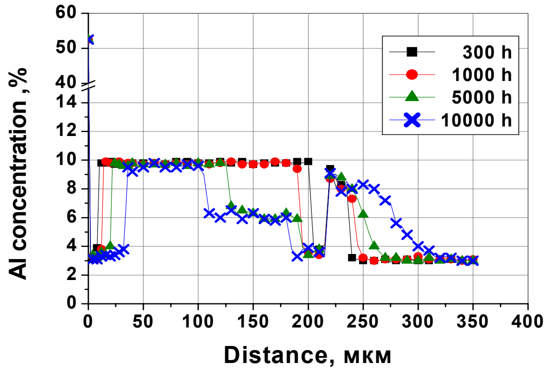

Fig. 5. Al concentration distribution across the coating layer [NiCoCrAlYRe (Sicoat 2464) coating after exposition at 950°C]

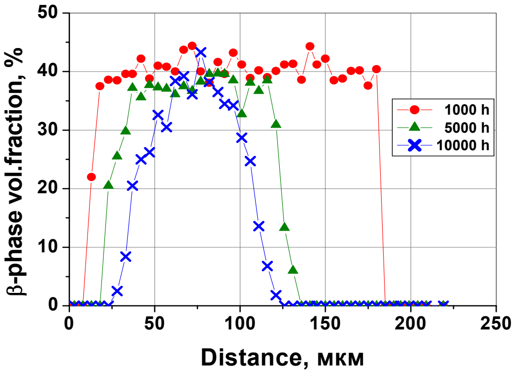

Fig. 6. The β-phase volume fraction distribution across the coating layer (different duration of exposure at 950°C)

expositions that must produce meaningful results for the sought parameters.

X-ray and metallographic analysis method

The experimental data required for the above calculations for the MeCoCrAlY coatings include:

- determination of the Al concentration distribution across the coating layer using X-ray micro analysis method;
- determination of the β-phase volume fraction change across the coating layer using Digital Optical Metallography (for example with the software made by "Ista-VideoTest");
- measurements of the oxide film thickness on the surface of the coating, and inner and outer de-alloyed layers thicknesses (Fig.3)

This experimental data should be obtained for at least three different temperatures in the range of the real gas turbine operation conditions with several time exposures that should bring meaningful results.

For the coatings of a different type, an element sensible to the working temperature history should be taken as a diffusing element.

Some illustrative examples of the NiCoCrAlReY coating study on the alloy Rene80 can be seen on the Fig. 4-5. The samples were isothermally exposed for the times up to 20000 hrs. at the temperatures (900–980°C). From the Fig.4 it can be seen that on the surface (up to 40 mkm depth) and at the interface coating-alloy (at 180–220 mkm) the formation of a de-alloyed layer is observed.

Conclusion

The new method of the coated blades remaining life time determination was developed for the stationary conditions. This method requires one blade removal from the turbine after a long operation time, metallographic analysis and calculations using the data obtained from the laboratory experiments performed in advance.

The method is based on the Larson-Miller dependence, the law of linear summation of damages, and the assumption that elements-distribution in the diffusion layer of the coating does not depend on the sequence of the temperature-time conditions.

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