

# A NEW METHOD FOR DETERMINING THE REMAINING LIFETIME OF COATED GAS-TURBINE BLADES

## NOVA METODA ZA IZRAČUN PREOSTALE TRAJNOSTNE DOBE LOPATIC PLINSKIH TURBIN

Leonid Borisovich Getsov<sup>1</sup>, P. G. Krukovski<sup>2</sup>, N. V. Mozaiskaja<sup>1</sup>,  
Aleksander I. Rybnikov<sup>1</sup>, K. A. Tadjia<sup>2</sup>

<sup>1</sup>NPO ZKTI Russian, <sup>2</sup>ITTPh NAN Ukraina  
guetsov@yahoo.com

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In the course of the exploitation of gas-turbine units (GTE) their turbine blades accumulate defects. These defects result from both the static stress caused by the 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 a determination of the remaining lifetime. Unfortunately, in many cases, at the moment when a GTE is stopped for maintenance, the thermal conditions of the previous exploitation of the blades are unknown.

In this presentation a new method of determining the remaining lifetime for coated blades is considered. A long-term strength-decay evaluation is carried out on the basis of the equivalent exploitation temperature  $T_{eq}$ , the known exploitation time  $\tau$  and the static stresses  $\sigma$ .

Key words: Larson-Miller dependence, turbine blade, remaining lifetime, coating, diffusion, equivalent temperature

Med uporabo plinskih turbin (GTE) se v lopaticah kopičijo napake. Te so posledica statičnih napetosti zaradi centrifugalnih in termo-cikličnih napetosti. Ker plinske turbine obratujejo v spremenljivih razmerah, časa eksploatacije ni mogoče upoštevati kot zanesljivega parametra za določitev preostale trajnostne dobe. Na nesrečo v mnogih primerih, ko je GTE ustavljena zaradi vzdrževanja, niso poznane termične razmere prejšnje uporabe lopatice.

V tem sestavku predstavljamo novo metodo za določanje preostale trajnostne dobe za lopatice s prekritjem. Ocena dolgotrajnega zmanjšanja trdnosti je izvršena na podlagi ekvivalentne temperature uporabe  $T_{eq}$ , znanega časa uporabe  $\tau$  in statičnih napetosti  $\sigma$ .

Ključne besede: Larson-Miller odvisnost, turbinska lopatica, preostala trajnostna doba, pokritje, difuzija, ekvivalentna temperatura

### 1 MAIN THESES

Four different cases can be considered:

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

In recent works <sup>1-6</sup> the surface-layer processes in the blades were investigated as a function of the long exposures to 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

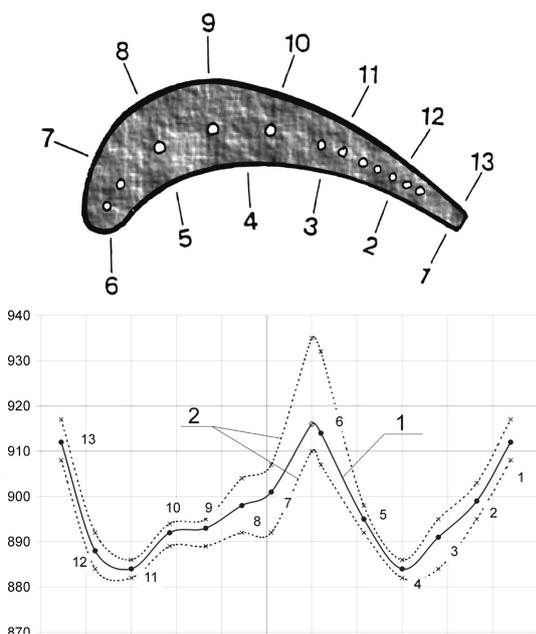
can be found using an X-ray analysis and a quantitative metallographic analysis of the blade, taken out from the engine. These calculations are based on the temperature dependences of the coating elements' diffusion characteristics. In this way, for example, an evaluation of the average operating temperatures of the coating, type NiCoCrAlY with the initial concentration of the  $c(\text{Al}) = 8.4\%$ , was performed <sup>6</sup> – **Figure 1** (cooled blades, IN738 alloy; worked for 26 400 h in the turbine).

### 2 DETERMINATION OF $T_{eq}^{\sigma}$

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

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

1. The remaining lifetime of the blade is determined by the remaining lifetime of its bulk metal;
2. The temperature of the blade cross-section is supposed to be constant and it corresponds to the maximum



**Figure 1:** Working temperature (°C) distribution around the cross-section contour after exploitation for 26 400 h. The numbered points on the plot correspond to the numbered positions on the blade. Curve 1 – calculated; curves 2 – error range of measurements.

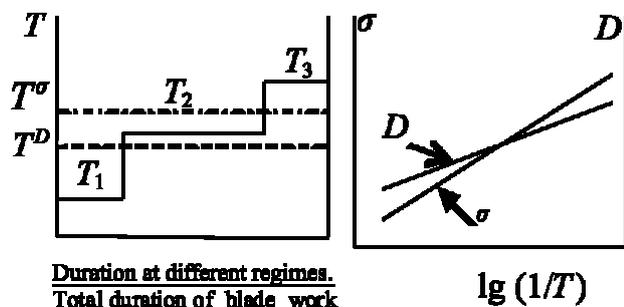
**Slika 1:** Porazdelitev delovne temperature (°C) vzdolž oboda preseka po 26 400 h eksploatacije. Oštevilčene točke označujejo oštevilčene točke na lopatici. Krivulja 1 – izračunano, 2 – območje merilne napake.

temperature value in the maximally loaded cross-section;

3. The damages for different temperatures and different stresses are summed according to a linear law and at the moment of destruction the following relationship is true:

$$\sum(\tau_i/t_i) = 1 \tag{1}$$

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



**Figure 2:** The diagram of the change of temperature during operation (a) and the temperature dependences of long durability and the factors of diffusion (b)

**Slika 2:** Diagram spremembe temperature med operacijo (a) in temperaturna odvisnost dolge trajnosti in difuzijski faktorji (b)

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

Let us use the Larson-Miller dependence:

$$P(\sigma) = T(C + \lg t) \tag{2}$$

where  $t$  is the time of destruction at the temperature  $T$  and stress  $\sigma$ . 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):

$$\begin{aligned} t_1 &= 10 [P(\sigma_1)/T_1] - C ; t_2 = 10 [P(\sigma_2)/T_2] - C ; \\ t_3 &= 10 [P(\sigma_3)/T_3] - C ; t_4 = 10 [P(\sigma_4)/T_4] - C ; \\ t_5 &= 10 [P(\sigma_5)/T_5] - C \dots \end{aligned} \tag{3}$$

where  $\sigma_i$  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 the different operation regimes  $\tau_1 : \tau_2 : \tau_3 : \tau_4 : \tau_5$  etc.

The value of the equivalent temperature  $T_{eq}$  can be obtained from the dependences:

$$\begin{aligned} T_{eq}^\sigma &= \frac{2,3P(\sigma_{eq})}{\ln\left(\sum \tau_i / \sum \tau_i \exp\left(-2,3P(\sigma_{eq})/T_i\right)\right)} \\ P(\sigma_{eq}) &= T_{eq}^\sigma (C + \lg \tau_{peq}) \\ \sum \frac{\tau_i T_i}{P(\sigma_i) - CT_i} &= 1 \end{aligned} \tag{4}$$

which parameters are values of the operating time  $\tau_1 : \tau_2 : \tau_3 : \tau_4 : \tau_5$  etc. by the various power settings characterized by the values  $T_i$  and  $\sigma_i$ . Here,  $P(\sigma_{eq})$  – parameter of dependence of Larson-Miller. Thus, the remaining lifetime of the blades 2–4 after the turbine operation during the time  $\tau$  can be determined for the stress  $\sigma_{eq}$  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  $T_{eq}^\sigma$  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 lifetime. Thus, the calculated  $T_{eq}^\sigma$  is based on the time ratio  $\tau_1 : \tau_2 : \tau_3 : \tau_4 : \tau_5$  etc., but in most cases this ratio is unknown. For a determination of the real (objective) ratio  $\tau_1 : \tau_2 : \tau_3 : \tau_4 : \tau_5$  etc. the calculated  $T_{eq}^D$  can be used.

### 3 METHOD OF DETERMINING THE WORKING-TIME RATIO 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  $T_{eq}^D$  can be determined. This temperature ( $T_{eq}^D$ ) will be equivalent to the average temperature determined using the Al diffusion parameters. It can be used as an equivalent temperature for the determination of the residual corrosion lifetime of the coating. But for the determination of the blade's remaining lifetime under applied stress (centrifugal bending stress, or especially thermo-cyclic stress), this temperature ( $T_{eq}^D$ ) 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  $T_i$  and times of exploitation  $\tau_i$ , the distributions of the Al and oxide layer thickness can be obtained (corresponding to the exploitation times). By comparing this data with the calculated  $T_{eq}^D$  for the different points of the profile (Figure 1), the ratio of times  $\tau_1 : \tau_2 : \tau_3 : \tau_4 : \tau_5$  etc. can be obtained.

### 4 METHOD OF $T_{eq}^D$ DETERMINATION

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

The oxide  $Al_2O_3$  is formed during the blade exploitation by a combination of Al and oxygen absorbed from the gas environment and diffused through the oxide layer ( $x_1 - x_0$ ) to the oxide-coating interface marked as  $x_1$ . The diffusion of Al from the coating occurs in two directions:

- to the oxide-coating interface  $x_1$ , where it reacts with diffused oxygen;

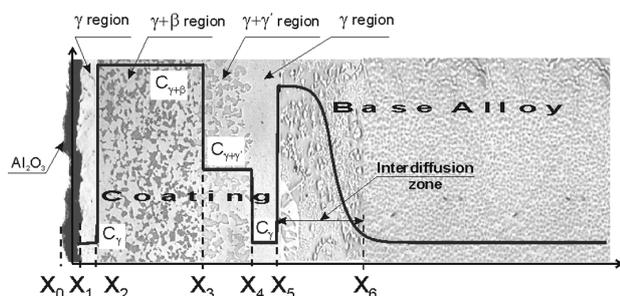


Figure 3: Typical Al concentration distribution in the coating layer and the bulk alloy

Slika 3: Tipična porazdelitev koncentracije Al v plasti pokritja in v zlitini

- 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 into the bulk alloy or into the coating.

Due to the Al diffusion from the  $\gamma + \beta$  two-phase coating region, the depleted Al single-phase zones with a reduced concentration of Al ( $\gamma$ -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, Figure 2). All Al, diffused from the coating, is diffused from the  $\gamma + \beta$  two-phase coating region due to the disappearance (consumption) of the  $\beta$ -phase. The Al concentration curve in the MeCrAlY coating has the shape of a stepped line, and in the bulk alloy region – a 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:

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

$$\tau > 0 \quad x_1 < x < x_\infty \quad C = C(x, \tau)$$

$$W = W(x, \tau) \quad D_{\text{eff}} = D_{\text{eff}}(x)$$

$$x_1 = x_1(\tau) \quad x_2 = x_2(\tau) \quad x_3 = x_3(\tau) \quad x_5 = x_5(\tau)$$

with the initial condition:

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

the boundary condition for infinity:

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

and the boundary condition on the moving interface  $x_1$ , describing the diffusion flux (due to the concentration gradient) of the Al from the coating to the left (Figure 3), forming the oxide:

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

The flux (8) conjointly with the flux  $C(x_1, \tau)(dx_1/d\tau)$  (formed by moving the interface  $x_1$  to the right) produce the total Al flux, which creates an oxide film with a thickness of  $\Delta x$ . The kinetics of the oxide film growth can be described with two parabolic equations:

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

where  $k_{ox}^*$ ,  $k_{ox}^{**}$  – are the coefficients of the oxide-film-growth intensity (the so-called constants of oxidation),  $\tau^*$  – boundary time point, before it the kinetics obey the oxidation law (9), after – the oxidation law (10). The curves (9) and (10) for intersect at the time point  $\tau^*$ ;  $\tau^0$  – time point (negative value) of the intersection for the curve (10) and the time axis  $\tau$ . The

necessity of using two parabolic laws (9) and (10) for the description of the Al-oxide growth can be explained by the faster formation (growth) of the  $\theta$ -oxide phase before the time point  $\tau^*$ , and by the slower growth of the  $\text{Al}_2\text{O}_3$   $\alpha$ -oxide phase for  $\tau > \tau^*$ . The coefficients  $k_{\text{OK}}^*$ ,  $k_{\text{OK}}^{**}$ ,  $\tau^0$  and the value  $\tau^*$  in (9) and (10) are determined from the experimental data of the oxide growth as a function of time.

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

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

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 the diffusion of Al to the bulk alloy can be written as:

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

According to the physical model (**Figure 3**), the flux of the 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.:

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

where  $W$  is the 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  $\tau_D^0$  in (14) are determined from the experimental data of the diffusion-zone increase with time.  $\Delta y = x_5 - x_4$  – the 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 the 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:

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

According to the physical model, all the Al outgoing from the coating, actually outgoes from the  $\gamma + \beta$ -two-phase coating zone by consuming the  $\beta$ -phase. Then the movement of the boundaries  $x_2$  and  $x_3$ , and the Al concentration decrease in the  $\gamma + \beta$ -two-phase zone can be described by the equation of the mass balance between the Al diffusion fluxes through these boundaries

and for the diffusion fluxes due to the Al concentration differences in the  $\gamma + \beta$ - and  $\gamma$ -phases ( $\Delta C = C_{\gamma+\beta} - C_\gamma$ ):

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

where  $J_\gamma(x_{2-}, \tau) = -D_{\text{eff}} \frac{dC(x_{2-}, \tau)}{dx}$

and  $J_\gamma(x_{3+}, \tau) = -D_{\text{eff}} \frac{dC(x_{3+}, \tau)}{dx}$

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  $x_3$ , respectively.

The expression (17) after dividing by  $J_\Sigma$  takes the form:

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

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

$$g_2 = k_2 \cdot \frac{\Delta C}{C_n^0} \quad g_3 = k_3 \cdot \frac{\Delta C}{C_n^0} \quad (19)$$

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

$$\begin{aligned} \frac{dx_2}{d\tau} &= J_\Sigma \frac{k_2}{C_n^0} \quad \frac{dx_3}{d\tau} = J_\Sigma \frac{k_3}{C_n^0} \\ \frac{dC_{\gamma+\beta}}{d\tau} &= J_\Sigma (x_3 - x_2) (1 - g_2 - g_3) \end{aligned} \quad (20)$$

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 times of the tests or exploitation.

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

$$C_{\gamma+\beta}(\tau) = C_\beta(\tau) \cdot C_\beta^{\text{Al}} + [1 - C_\beta(\tau)] C_\gamma \quad (21)$$

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

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

Al accumulated in the diffusion zone partially diffuses back into the coating, due to the absence of the Al-concentration space gradient.

The Al accumulated in the diffusion zone partially diffuses back into the coating, due to the gradient in the concentration to the right of the border  $x_4$ . The related diffusion flux:

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

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 us to calculate the Al concentration distribution in the coating and in the base blade material,  $T_{\text{eq}}^D$  and time ratios  $\tau_1 : \tau_2 : \tau_3 : \tau_4 : \tau_5$  etc. in the cooled blades for different operation modes. In the case of the 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  $\tau_1 : \tau_2 : \tau_3 : \tau_4 : \tau_5$  etc.

## 5 ALGORITHM FOR THE CALCULATION OF THE RESIDUAL LIFE TIME

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

1) determination of the parameters of diffusion for the blade coating by means of experiments and calculations,

2) experimental determination of the 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  $T_{\text{eq}}^D$  according to a special method based on the solution of the reverse diffusion problem for experimental data on the distribution of aluminium (see step 2),

4) calculation of the allocation of the time of GTE operation in different modes  $\tau_1 : \tau_2 : \tau_3 : \tau_4 : \tau_5$  etc. =  $r_1 : r_2 : r_3 : r_4 : r_5$  etc., corresponding to the power values  $N_1, N_2, N_3, N_4, N_5$  etc. (operation time  $\tau = a \sum r_i$ , a  $\tau_i = ar_i$  according to the data obtained during the step 2,

5) calculation of the equivalent temperature  $T_{\text{eq}}^\sigma$  using equation (4)

6) calculation of residual lifetime of the set of blades (after the operation during the time  $\tau$ ).

The algorithm of the solution of the problem mentioned in 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  $\tau_i$  (in different modes) as a result of which we obtain the relevant distributions of aluminium and the width of the oxide layer, corresponding to the operation times. Having these set of points for different conditions we chose those in which:

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

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

In other words:

1. Knowing  $T_{\text{eq}}^D$  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 operating modes contributing to the resulting distribution curve

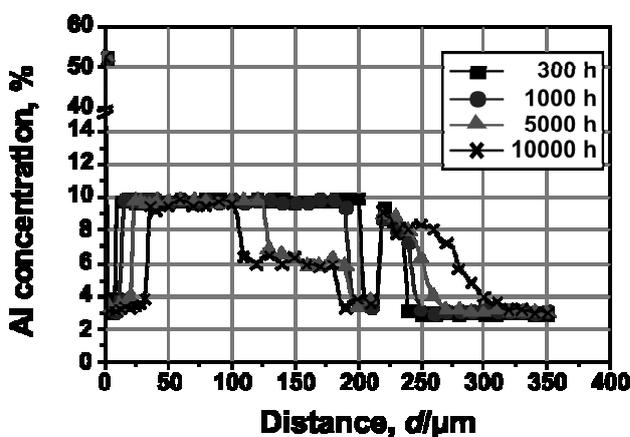
$$F_1(\tau, T_{\text{eq}}^D) = \sum F_1(\tau_i, T_i^D) \quad (22)$$

2. Knowing  $T_{\text{eq}}^D$ , we obtain a number of possible values  $\tau_i - T_i^D$  from the equation (22).

3. Knowing different values  $T_{\text{eq}}^D$  for different blade points we find the true values  $\tau_i - T_i^D$  from the equation (22).

4. Having found the true values  $\tau_i - T_i^D$  (step 3), we determine the value  $T_{\text{eq}}^\sigma$  using the formula (4).

The residual lifetime of the set of blades (after the operating time  $\tau$ ) is calculated as the time value before fracture at the temperature  $T_{\text{eq}}^\sigma$  under the stress  $\sigma_{\text{eq}}$ , multiplied by the strength safety factor (obtained in the course of the strength calculations for blades at the design stage or by the safety factor chosen from the strength standards) minus the elapsed operating time  $\tau$ .



**Figure 4:** Al concentration distribution across the coating layer [NiCoCrAlYRe (Sicoat 2464) coating after exposition at 950 °C]

**Slika 4:** Porazdelitev koncentracije Al na prerezu plasti pokritja [NiCoCrAlYRe (Sicoat 2464) pokritje po žarjenju pri 950 °C]

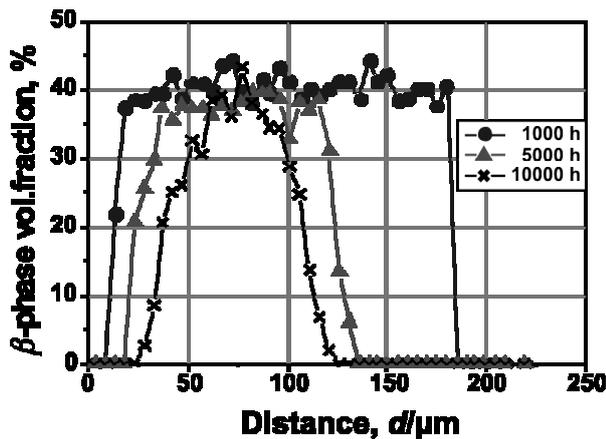


Figure 5:  $\beta$ -phase volume fraction distribution across the coating layer (different duration of exposure at 950 °C)

Slika 5: Porazdelitev volumskega deleža  $\beta$ -faze (različno trajanje žarjenja pri 950 °C)

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 the Al concentration distribution on the basis of the coating-layer thickness using the X-ray microanalysis method;
- determination of the volumetric share of the  $\beta$ -phase on the basis of the 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 the 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 exposures that must produce meaningful results for the sought parameters.

## 6 X-RAY AND METALLOGRAPHIC ANALYSIS METHOD

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

- a determination of the Al concentration distribution across the coating layer using the X-ray microanalysis method;
- a determination of the  $\beta$ -phase volume-fraction change across the coating layer using Digital Optical Metallography (for example with the software made by "IstaVideoTest");
- measurements of the oxide film thickness on the surface of the coating, and the inner and outer de-alloyed layers thicknesses (Figure 3).

This experimental data should be obtained for at least three different temperatures in the range of the real gas-turbine operating 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 in Figure 4–5.

The samples were isothermally exposed for times up to 20 000 h at the temperatures 900–980 °C. From Figure 4 it can be seen that on the surface (up to 40  $\mu\text{m}$  depth) and at the interface coating-alloy (at 180–220  $\mu\text{m}$ ) the formation of a de-alloyed layer is observed.

## 7 CONCLUSION

A new method of determining the remaining lifetime of coated blades was developed for stationary conditions. This method requires one blade's removal from the turbine after a long operating 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 the elements-distribution in the diffusion layer of the coating does not depend on the sequence of the temperature-time conditions.

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