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THE INFLUENCE OF LONG-TERM SERVICE EXPOSURE ON THE STRUCTURE AND PROPERTIES OF HIGH-TEMPERATURE STEELS AND ALLOYS

VPLIV DOLGOTRAJNEGA OBRATOVANJA PRI VISOKIH TEMPERATURAH NA LASTNOSTI JEKEL IN ZLITIN, NAMENJENIH UPORABI V ENERGETSKIH NAPRAVAH

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The results of studies on the mechanical properties, long-term durability, thermal fatigue resistance and microstructure of metal blades made from various steels and Ni-based superalloys after long-term (up to 100,000 h) main-gas-line exposure conditions are presented. The data were developed and the calculations of the stress-strain state of the blades were used as the basis for a proposal for their projected lifetime. An extrapolation method using long durability curves based on a lifetime of 300,000 h was developed and is illustrated with an example of a 12 % Cr steel.

Key words: steels and Ni superalloys, long-term exposure to high temperatures, mechanical properties, microstructure, durability and life-time prediction.

V prispevku so predstavljeni rezultati študije mehanskih lastnosti pri dolgotrajni izpostavljenosti visokim temperaturam in odpornost proti termičnemu utrujanju kot tudi mikrostruktura turbinskih lopatic, izdelanih iz različnih vrst jekel in Ni-superzlitin po dolgotrajnem (do 100.000-urnem) obratovanju v seriji plinskih turbin. Ugotovljeni eksperimentalni rezultati in izračuni napetostno-deformacijskega stanja turbinskih lopatic so bili uporabljeni kot osnova za projekcijo njihove preostale trajnostne dobe. Razvita je bila ekstrapolacijska metoda, ki uporablja krivulje dolgotrajne izpostavljenosti do 300.000 h. Prikazan je primer za jeklo z 12 % Cr.

Ključne besede: jekla in Ni-superzlitine, turbinske lopatice, dolgotrajno obratovanje pri visokih temperaturah, mehanske lastnosti, mikrostruktura, napoved trajnostne dobe

1 INTRODUCTION

Long-term continuous service under high temperatures can result in considerable changes to a material's characteristics. These changes in the material's characteristics can be taken into account with the help of the structural parameters, depending on the temperature and the elapsed service time [1]. Therefore, the ultimate tensile strength, σ_B, the yield strength, $\sigma_{0.2}$, the plasticity, δ, the creep rate, $p^{\bullet}$, the creep cracks' growth rate, $dl/d\tau$, the resistance to cyclic deformation, $S_{0.4}$, the resistance to thermal fatigue, $\Delta\varepsilon$, and the long-term strength, $\sigma_{l.d.}$, depend on the service conditions according to the formulae (1)–(8):

$$\sigma_B = F_1(s_1(\tau,T), s_2(\tau,T), s_3(\tau,T), ...T, v) \quad (1)$$

$$\sigma_{0,2} = F_2(s_1(\tau,T), s_2(\tau,T), s_3(\tau,T), ...T, v) \quad (2)$$

$$p^{\bullet} = F_3(s_1(\tau,T), s_2(\tau,T), s_3(\tau,T), ...T, \sigma) \quad (3)$$

$$\sigma_{l.d.} = F_4(s_1(\tau,T), s_2(\tau,T), s_3(\tau,T), ...T, \tau) \quad (4)$$

$$\delta = F_5(s_1(\tau,T), s_2(\tau,T), s_3(\tau,T),... T, v) \quad (5)$$

$$\Delta\varepsilon = F_6(s_1(\tau,T), s_2(\tau,T), s_3(\tau,T),... T_{max}, T_{min}, N, \tau_c) \quad (6)$$

$$S_{0,4}= F_7(s_1(\tau,T), s_2(\tau,T), s_3(\tau,T), ...T, v) \quad (7)$$

$$dl/d\tau = F_8(s_1(\tau,T), s_2(\tau,T), s_3(\tau,T),... T, K_1) \quad (8)$$

Here, v is the deforming rate, τ_c, T_{max}, T_{min}, N are the cycle duration, the maximum and minimum temperatures of a cycle, the number of cycles before the formation of thermal fatigue cracks by thermocyclic loading, and K_1 is the stress-intensity factor. For the estimation of SSS and safety factors for components made of this alloy, taking into account its structural changes, it is necessary to know the kinetics of the characteristic changes during long-term exposure to high temperatures.

This paper presents the results of a study of the behavior of the mechanical properties and long-term strength on the background of structural changes taking place in the course of the long-term service for alloys used for the blades of gas turbines in the gas-compressor units operating at compressor stations (CSs).

2 EXPERIMENTAL PROCEDURE

2.1 Materials and method

The changes in the structure and the properties of the metal of gas-turbine blades made in EP428 steel and the nickel-based alloys EI893, ZMI-3U, EI929, CNK-7, IN738 (see **Table 1**), taking place in the course of long-term service were studied.

Table 1: Chemical composition of the materials (mass fraction, %)
Tabela 1: Kemična sestava preiskovanih materialov (masni delež %)

Alloy	C	Cr	Co	W	Mo	Nb	Ti	Al	V	Ta	Ni	Fe
IN738 LC	0.11	15.7–16.3	8.0–9.0	2.4–2.8	1.5–2.0	0.6–1.1	3.4	3.2–3.7		1.5–2.5	base	
ZNK-7	0.06–0.12	14–15.5	8–9.5	6.2–7.5	0.2–0.6	–	3.6–4.4	3.4–4.5	–	–	base	
ZMI-3U	0.07–0.15	12.5–14	4–6	6.5–8	0.5–2	0.1	4–5.5	2.8–4	–	–	base	
EI893	<0.07	15–17	–	8.5–10	–	–	1.2–1.6	1.2–1.6	–	–	base	<3
EI929	<0.12	9–12	12–16	4.5–6.5	4–6	3.5–4.5	1.4–2	3.6–4.5	0.2–0.8	–	base	<5
EP428	0.17–0.23	10.5–12.5	–	0.7–1.1	0.5–0.7	–	–	–	0.15–0.3	–	0.5–0.9	base

The following parameters describing the structural conditions of the materials were used:

- composition, amount and size of the carbide and carbonitride phases,
- particles' composition and the amount of matrix phase,
- composition, sizes of particles and the amount of intermetallic phases,
- lattice-period mismatch of precipitated phases and matrix,
- amount, composition and form of particles of topologically closely packed (TCP) phases,
  phase structure of grain boundaries.

The changes of these blade-metal parameters in the course of long-term service have been chosen as a basis for the approximation of the functions $s_1(\tau,T)$, $s_2(\tau, T)$, $s_3(\tau, T)$ etc.

The following research methods were applied: optical black-and-white and color metallography, optical metallography with the use of selective etching methods (detection of delta-ferrite and carbides $M_{23}C_6$), translucent electron microscopy, analytical high-resolution electron microscopy with the use of an energy-dispersion spectrometer (EDS), electron-energy-losses spectrometer (EELS) and an inclusions analyzer using phase contrast (HAADF), and phase analysis. The electron microscope-aided examination was carried out using extraction coal replicas and thin metal papers. The experiments for the determination of the mechanical properties, including long-term tensile strength, were carried out in compliance with standard procedures, and the thermal fatigue resistance – according to the procedure [2] – for samples made of blades dismantled after long-term service.

2.2 The structure and the properties of blades made of the steel EP428

The samples made of both fin and mounting parts of the blades made of EP428 steel were examined. The temperature during the service of these blades was 500 °C and ≈400 °C, according to [3]. It was found that after the service period of 100,856 h the average area of the particles of carbides, $M_{23}C_6$, in the fin part turned out to be 11 % higher than the average area of these particles in the mounting part of the blade. The values of the particle density of their volumetric share in the fin part metal turned out to be 12 % less than in the metal of the mounting part of the blade. In the fin area of the blades some increase (by 12.7 %) of the sizes of carbides, $M_{23}C_6$, on the grain boundaries was observed in comparison with the sizes of analogous carbides in the area of the mounting part. Thus, it was found that after long-term service of the blades the coagulation of carbides, $M_{23}C_6$, at the grain boundaries and in the grain takes place. The ratio w(Cr/Fe) (parameter s_1) in the carbide, $M_{23}C_6$, (**Figure 1**) and the ratios in carbo-nitride phases Me_2X (parameters s_2 and s_3) were found to be sensitive to the long-term service. The character of the relationship w(Cr/Fe) from the elapsed service time, τ, can be described by the following expression

$$w = w_0(1 + \alpha\tau) \quad (9)$$

where $w_0 = 3.0$ and $\alpha = 4 \cdot 10^{-6}$ for the temperature 500 °C.

As the relationships w(Cr/V) and w(V/N), they cannot be described mathematically so far due to the lack of obtained experimental data.

The data obtained from the tests of mechanical properties of the metal that had worked for a long period have not shown any major changes in comparison with

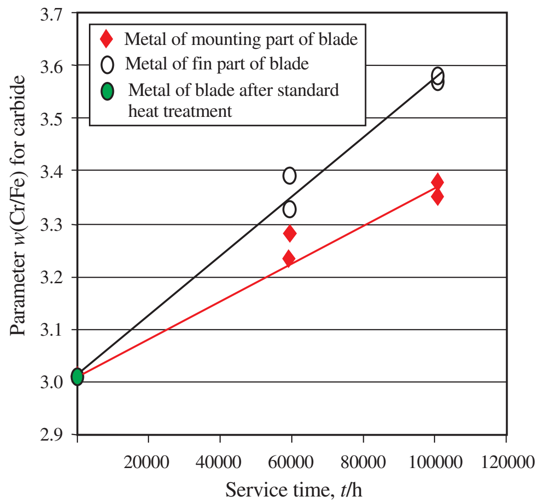

Figure 1: Dependence of the parameter w(Cr/Fe) of the metal from different parts of low-pressure turbine blades on the service time
Slika 1: Odvisnost med masnim razmerjem w(Cr/Fe) v $M_{23}C_6$ karbidih od časa obratovanja različnih delov nizkotlačnih turbinskih lopatic

the initial condition of the metal. At the same time the long-term strength tests (**Figure 2**) have shown that after long-term service the slopes of curves change. This change of the slopes of the curves is caused by the above-described structural changes in the material. Thus, if in relationship (4) we use the curve slope as the structural parameter s_1, then the obtained data describing the relationship of the changes of the value w(Cr/Fe) in the carbide, $M_{23}C_6$, on the service time allows us to find out the structure of the long-term strength as a function of the blades' service time at a temperature of 500 °C, taking into account the relationships (9). They are represented as a fan of curves, according to the scheme shown in **Figure 3** [4]. Let us use the power relationship of time-to-fracture from temperature $\tau_p = A\sigma^{-m}$, where m is a constant that depends on the time of service. Taking into account that the relation (9) for steel EP428 is linear, we gain an opportunity to describe the relationship of m from the service time as $m = m_0(1–\alpha t)$. It can be seen that the experimental data for the metal after 60,000 h of service fit well with the calculated line 2, shown in **Figure 2**. Thus, it is reasonable to extrapolate the passport curve in the **Figure 2**, not with the help of the linear law in logarithmic coordinates, but according to the scheme shown in **Figure 3**, with slope modifications due to structural changes. The change of slope of the long-term strength curve of steel and introducing the parameters of the relation (9) have allowed us to adjust the extrapolation segment of the long-term strength stress (see curves 4 and 5 in **Figure**

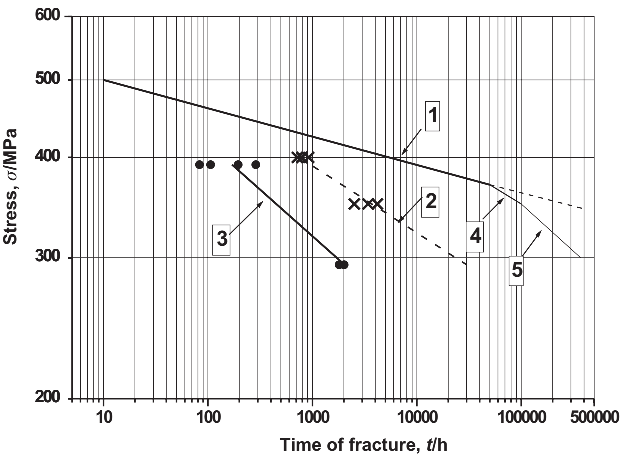

Figure 2: The long-term strength of blades made of steel EP428 under 500 °C

1 – passport long-term strength curve of metal with $\sigma_{0.2}$ = 700–750 MPa
2 – calculated curve for metal after service for 60,000 h
3 – **x**, **•** – experimental data for metal after service for 60,000 h and 100,000 h
4, 5 – segments of the extrapolated long-term strength curve (4 is parallel to 2, and 5 is parallel to 3).

Slika 2: Čas do porušitve turbinskih lopatic, izdelanih iz jekla EP428 v odvisnosti od trdnosti pri obratovanju pod 500 °C

1 – krivulja trajne statične trdnosti za jeklo s $\sigma_{0.2}$ = (700–750) MPa
2 – izračunana krivulja za jeklo po 60 000-urnem obratovanju
3 – **x**, **•** – eksperimentalni podatki za material po 60 000- in 100 000-urnem obratovanju
4, 5 – segmenti ekstrapolirane krivulje trajne statične trdnosti (4 je vzporedna 2, 5 je vzporedna 3).

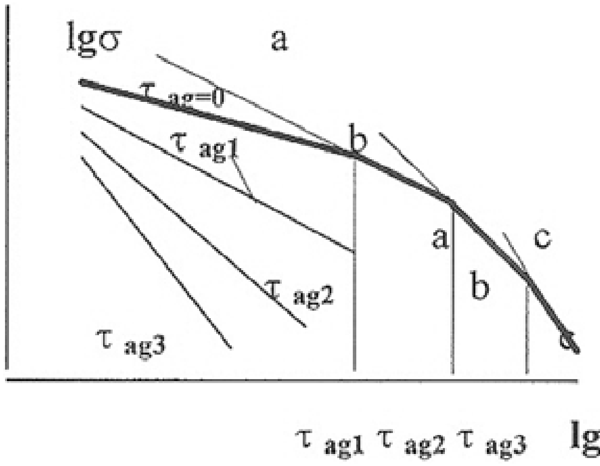

Figure 3: Schematic representation of the method of extrapolation. Vertical lines represent the stage of softening of the material during the aging process (Lines bb and τ_{ag1}, cc and τ_{ag2}, dd and τ_{ag3} are parallel)

Slika 3: Shematična predstavitev metode ekstrapolacije. Navpične linije pomenijo stadij mehčanja materiala med staranjem (linije bb in τ_{ag1}, cc in τ_{ag2}, dd in τ_{ag3} so vzporedne)

2). As a result it was found that the long-term strength σ_{200000} of the steel EP 428 under 500 °C is not 360 MPa, but 320 MPa.

2.3 Structure and properties of blades made of nickel-based alloys.

For nickel-based high-temperature alloys the long-term service leads to a considerable change in the quantity and size of particles of γ'-phase in the blade metal. This allows us to accept them as structural parameters, determining the changes of mechanical properties, thermal fatigue resistances and long-term

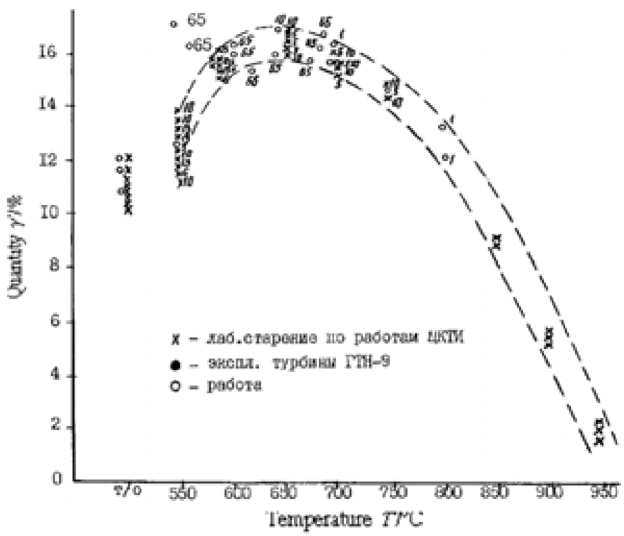

Figure 4: Influence of temperature on quantity of γ' – phase in the alloy EI893 after long-term blade service

Slika 4: Vpliv temperature na količino faze γ' v zlitini EI893 po dolgotrajnem obratovanju turbinskih lopatic

Table 2: Change of quantity of γ'-phase during the long-term service of blades made of alloy EI893
Tabela 2: Sprememba količine faze γ' med dolgotrajnim obratovanjem turbinskih lopatic, izdelanih iz zlitine EI893

GTE	Elapsed service time, h	Quantity of γ'-phase in initial conditions	Quantity of γ'-phase in blades of 1st stage	Quantity of γ'-phase in blades of 2nd stage	Relative change of γ'-phase quantity	
					1st stage	2nd stage
GT-750-6	22430	9.5	14	-	1.47	
	30165	9	16.6	12	1.84	1.33
GTK-10	11300	11.4	17	-	1.49	
	20500	9.4	15.9	-	1.69	
GTN-9	65000	11.4	16.5	15.8	1.45	

strength of alloys in the relationships (1)–(5) as functions of temperature and service time. With the help of the phase analysis method the changes to the quantity of γ'-phase in the alloy EI893 were assessed after long-term service of the blades in different gas-turbine units (see **Table 1** and **Figure 4**).

To find the relationships of the phase changes in alloy EI893 the samples were held at temperatures in the range 550–750 °C for a long time. It was found that for temperatures lower than 650 °C the equilibrium in γ'-phase formation was not reached after 10,000 h of service.

Simultaneously, it is enriched with tungsten and molybdenum. Long-term aging in the interval 700–750 °C practically does not cause changes to the quantity of γ'-phase formed at the initial aging stages after the standard heat treatment. Some little changes of quantity of the carbide MC and boride M_5B_3 phases are observed, which, however, apparently cannot result in any major changes to the alloy properties. Also, the carbide (MC > $M_{23}C_6$ > M_6C > $M_{12}C$) and boride (M_5B_3 > M_3B_2) transformations were observed. The obtained results allow us, on the one hand, to carry out the certification of blades regarding their temperature history, and on the other hand, to specify the type of relationships of the structural parameter s_1 of mechanical properties, the thermal fatigue resistances and the long-term strength of the alloy on the temperature and elapsed service time.

Special attention should be paid to the blades made of the alloy EI893 undergoing long-term service at the temperatures 550–650 °C. In these conditions fine-dispersed particles of γ'-phase precipitate, which results, in the case of a low hardening temperature and tempering temperature of 800 °C, in a drastic increase in the hardness and an embrittlement of the alloy. Another factor influencing on the properties of structural changes of the alloy kept for a long time under the temperature range specified above is the process of long-range ordering of γ-phase similar to Ni_2Cr [9]. In the case of the absence of stress concentrators the high long-term strength of the alloy in the specified temperature range ensures reliability of the blades. However, the presence of concentrators may result in cracking in the conditions of stress relaxation due to the low long-term plasticity of the alloy EI893 in these conditions. Such cracks have been observed in the zone of holes in the blade fins made for binding wire (**Figure 5**) [3], and also on the bottom blade ridge.

During the long-term service of blades made of the alloy ZMI-3U there is an additional increase of γ'-phase that takes place (instead of 41–42 % in the initial condition, there is 43–45 % after service lasting 16 and 22 thousand of hours), along with some coagulation of particles of γ'-phase and additional, in comparison with the initial structure, precipitation of the carbide $M_{23}C_6$. The precipitation of particles of carbides takes place predominantly at the grain boundaries and around carbides, MC, and the initial particles of γ'-phase.

The structural changes of the metal in the blades made of the alloy EI929 were also studied in the course of long-term service. With the help of electron microscopy (see **Figure 6, 7**) we looked at the dimensions of the particles of γ'-phase as functions of the temperature and the elapsed time of the alloy service. It should be noted that the obtained relationships with the temperature are not monotonous functions.

The obtained data confirm the possible opportunity to use the average surface density of small-sized (n_S') and large (n_S'') particles of γ'-phase, the aggregate density of particles (n_S), the average size (d_{av}) of particles of γ'-phases and the average distance between particles of γ'-phases as structural parameters of the alloy.

In the blades made of the alloy IN738 after 23000–30000 h of service some needle precipitations of TCP-phases (see **Figure 7**) were observed. Thus, the

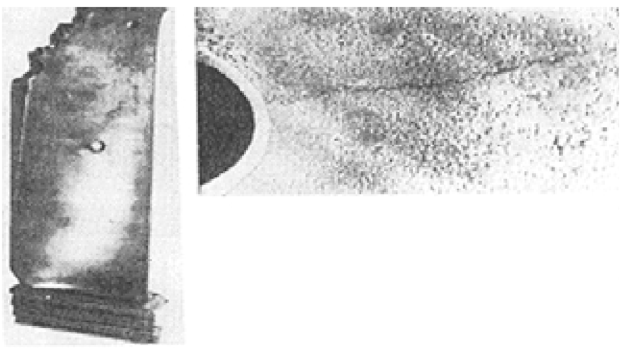

Figure 5: Crack in a hole for binding wire
Slika 5: Razpoka v luknji za povezovalno žico

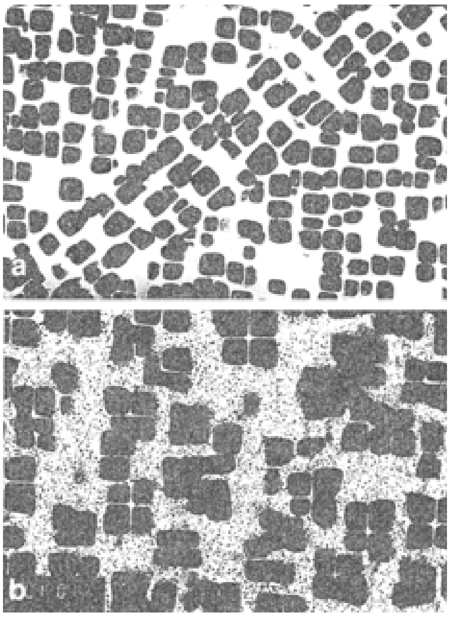

Figure 6: Electronic photos of microscopic structure of the blade mounting part (a) and front fin edge (b) made of the alloy EI929VD (after 31043 h of service)
Slika 6: Posnetek mikrostrukture montažnega dela lopatice (a) in rob prednjega dela repa (b), izdelanih iz zlitine EI929VD (po 31.043 h obratovanja)

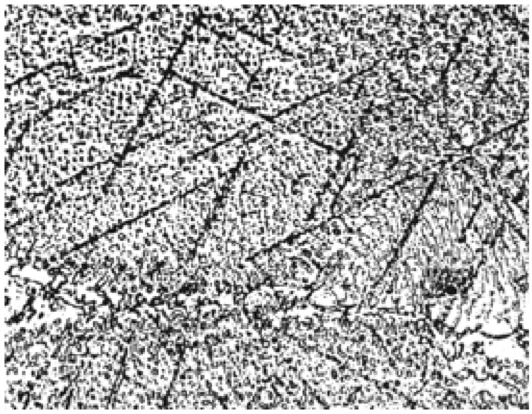

Figure 7: The microstructure of the metal of the blade made of the alloy IN 738 after being in service for 23,000 h, x100
Slika 7: Mikrostruktura turbinske lopatice iz IN 738 po 23.000 h obratovanja, povečava 100-kratna

research has allowed for a number of heat-resistant steels and alloys used for GTU blades to specify the structural parameters s_1, s_2, s_3, s_4 changing in the course of long-term service and determine the character of the relationships (1)–(7).

The **Tables 3 and 4** contain the results of mechanical tests of the blade metal relative units specifying the degree of influence of the service conditions.

Close examination of the results presented in **Tables 2 and 3** shows that while in service the strength properties of all the alloys at 20 °C either increase or remain the same, whereas the plasticity of the alloys, with rare

Table 3: Mechanical properties at 20 °C of the blade metal after long-term service in the relative coordinates
Tabela 3: Mehanske lastnosti turbinskih lopatic pri 20 °C po dolgotrajnem obratovanju, izražene v relativnih vrednostih

Alloy	GTE	Time of service, h	$\frac{\sigma_{0.2}^{fin}}{\sigma_{0.2}^{mount.p.}}$	$\frac{\sigma_B^{fin}}{\sigma_B^{mount.p.}}$	$\frac{\delta^{fin}}{\delta^{mount.p.}}$	$\frac{\Psi^{fin}}{\Psi^{mount.p.}}$
IN 738	GTK 25 I	24000	1.07	0.95	0.69	0.48
		30000	1.04	0.94	0.25	0.83
		55000	1.08	1.04	1.15	1.07
EI893	GT 750-6 (1 and 2-th stages)	20500	0.97	0.95	0.64	-
		52000	1.08	1.09	0.75	-
		54601	1.21 1.09*	1.15 1.07*	0.56 0.56*	0.54 0.57*
ZNK-7	GTK25 I	23000	1.08	1.06	0.18	0.67
ZMI 3U**	GTN-25-1	30000	0.92	0.93	0.65	1.1
ZMI 3U	GTK-25 IR	24000	1.13	1.13	0.65	0.39
EI 929	GTN-25-1	31043	1.14	1.0	0.46	0.45

Comment: *blades of the second stage, **guide blade

Table 4: Mechanical properties at 700 °C of the blade metal after long-term service in the relative coordinates
Tabela 4: Mehanske lastnosti turbinskih lopatic pri 700 °C po dolgotrajnem obratovanju, izražene v relativnih vrednostih

Alloy	GTE	Time of service, h	T_{test} /°C	$\frac{\sigma_{0.2}^{fin}}{\sigma_{0.2}^{mount.p.}}$	$\frac{\sigma_B^{fin}}{\sigma_B^{mount.p.}}$	$\frac{\delta^{fin}}{\delta^{mount.p.}}$	$\frac{\Psi^{fin}}{\Psi^{mount.p.}}$
IN 738	GTK 25 I	55000	750	0.99-1.08	1.0–1.06	1.48–3.0	1.44–1.45
EI893	GT 750-6	54601	750	0.9	0.84–1.0	1.23–1.55	1.3–1.35
ZNK-7	GTK 25 I	23000	700	1.0	1.0	1.25	2.0
EI929	GTN -25-1	40000	700	1.03	1.0	0.9	1.1
ZMI-3U	GTN-25 I	24000	750	1.04	1.06	1.0	0.5

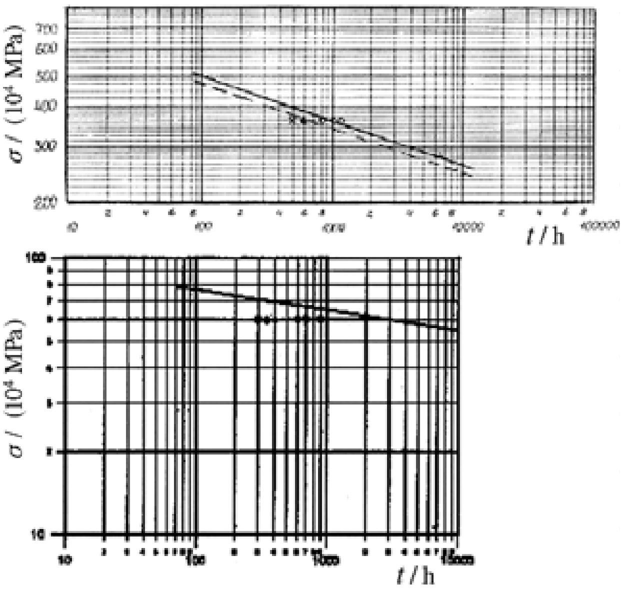

Figure 8: Long-term service influence on long-term strength of the alloys IN738 (a) and CNK-7 (b) – specification: experimental data for blade metal after operating time of 30,000 h

Slika 8: Vpliv dolgotrajnega obratovanja zlitin IN738 (a) in CNK-7 (b) na trajno statično trdnost – specifikacija, —- eksperimentalni podatki za 30.000-urno obratovanje turbinskih lopatic

exceptions, decreases. Under high temperatures, in contrast, the strength properties practically do not vary and the plasticity increases.

As can be seen in **Figure 3**, the rupture life of heat-resistant nickel-based alloys normally decreases after long-term service by a factor of 1.5–2 in comparison with the initial value.

It should be noted, however, that the **Figure 8** data were obtained using the samples cut out from the inner part (at some distance from the surface) of the blade fin; this is why the influence of decrease of doping material concentration and corrosion damages to the surface were not simulated during these tests. Also, some samples for the thermal fatigue tests (carried out according to procedure [2]) were cut out of the blades. It was found that in the metal of the blades made of the alloy ZMI 3U after 16153 h of service, in comparison with the data obtained for an alloy in the initial state, the thermal fatigue strength parameters do not change significantly.

3 ASSESSMENT OF RESIDUAL BLADE LIFE

The residual life assessment is usually done on the basis of normative safety factors for long-term strength, taking into account the resistances of the blade metal to low-cycle fatigue (thermal fatigue) and high-frequency fatigue. As in the process of assessment of the safety factor for the service duration in question one deals with values of destructive and working stresses, the precision of such an assessment depends on the precision of the assessment of these stresses. Above we have considered the approaches to the destroying stresses' assessment, taking into account the structural changes in the metal in the course of long-term blade service. The safety factors in the case of multi-mode service conditions ($i = 1\ldots n$ – the modes differing in temperatures and stresses) are determined by the following formula, based on the hypothesis of the linear summation of damages:

$$K = \left[\sum \left(\frac{1}{K_i} \right)^{m_i} \right]^{\frac{1}{m_{cp}}} \quad (10)$$

This formula can be used for cases of static, low-cycle and high-frequency fatigue failure, which are described by the following dependencies: $\tau_p \sigma^{m_c} = A$, $N\Delta\varepsilon^{m_T} = B$, $N\sigma_a^{m_o} = C$, where τ_p – time to failure, $\Delta\varepsilon$ is the amplitude of the total deformation in a cycle, σ_a is the stress amplitude, N is the number of cycles, and A, B, C, m_c, m_T, and m_y are constants.

The problem of assessment of the working stresses, calculated with the help of modern computational methods, e.g., the finite-element method, deserves special attention. The static stresses calculated in the design process are mainly assessed using the rod calculation scheme and were accepted as constant along the section, i.e., an average. The finite-element calculations of elastic stresses in the blades show that the stresses along the blade section are not constant values. For this reason the redistribution of stresses caused by creep was calculated. It was found that the stress relaxation during the service life does not ensure a decrease of stresses in the most stressed points down to the level of the average stresses. However, it was accepted to be useful to take into account the local stress values only for an estimation of the blade cyclic strength, and to do with average stresses for the calculation of the static strength of ductile materials. For low-ductility materials it is necessary to use the design values of local stresses, taking into account the creep.

4 CONCLUSIONS

A method for calculating the structural parameters of the equations describing the influence of temperature and service-time parameters on the properties of the materials of gas-turbine blades has been put forward.

1. Changes in the structure and properties of the steel EP428 and the alloys EI893, EI929, ZMI-3U, CNK-7, IN 738 occurring during long-term service have been found.

A method for extrapolation of the results of the test for long-term strength, taking into account changes to the structure of the heat-resistant alloys in the course of the long-term service life has been put forward

2. The basics of the procedure for the assessment of safety factors and the residual life of blades, taking into account the service time and temperature, have been developed

5 REFERENCES

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