OPTIMIZATION OF CONDITIONS OF REDUCTION HEAT TREATMENT OF BLADES OF ALLOY KhN65VMTYu AFTER LONG-TERM SERVICE

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Condition of the material of gas turbine engine blades after long-term service was studied and their repairability was determined. Parameters were developed for high-temperature heat treatment of alloy KhN65VMTYu (EI893) to extend the service life of product.

Keywords: *blades, reduction heat treatment, microstructure, physical-mechanical properties, extension of service life*

The blades of the first stage of turbine rotor, manufactured of alloy KhN65VMTYu (EI893) using method of hot stamping, were taken as objects of investigation at operating time of 53,000, 60,142 and 62,449 h. The blades can be in service for a long time (tens of thousands of hours) at high temperature of about 700–750 °C [1]. However, it inevitably results in structure-phase transformations affecting their serviceability. In the process of service the corrosion, erosion, static, thermal-fatigue and fatigue damages are accumulated.

The purpose of this work is to study the post service state of material of gas-turbine engine blades, passed long service period, to determine their repairability and possibility of restoration.

To recover the structure and properties of material of pilot blades the billets cut out of them were heat treated using different conditions [2, 3]:

- heating up to 1160 °C, holding for 2 h, air cooling + heating up to 1000 °C, holding for 4 h, air cooling + heating up to 900 °C, holding for 8 h + heating up to 820 °C, holding for 15 h, air cooling;
- heating up to 1160 °C, holding for 2 h, air cooling + heating up to 950 °C, holding for 6 h, air cooling + ageing at 820 °C for 12 h, air cooling;
- heating up to 1160 °C, holding for 2 h, air cooling + ageing at 800 °C for 12 h, air cooling;
- heating up to 1050 °C, holding for 3 h, air cooling + ageing at 850 °C for 12 h, air cooling;
- heating up to 1030 °C, holding for 2 h, air cooling + ageing at 850 °C for 12 h, air cooling;
- ageing at 750 °C for 24 h, air cooling.

To analyze the state of material the methods of optical metallography (microscope «Neophot-32») and scanning electron microscopy (VEGA/TESCAN) were used. The tensile tests of mechanical properties of flat specimens at room temperature were carried out in the rupture machine U10T. Microdeformations were determined using method of X-ray diffraction analysis in the diffractometer «Dron-3M» (applying Cu-K_α radiations in traditional geometry of Bregg–Brentano).

Using analysis of a sample the chemical composition of alloy was determined, wt.%: 16 Cr; 1.5 Al; 4 Mo; 1.45 Ti; 9 W; 0.5 Mn; 0.01 B; 3 Fe; 0.05 C. The chemical composition of material of blades was in compliance with standards established by TU 14-1-322–72 for the alloy KhN65VMTYu.

The microstructures of alloy KhN65VMTYu after different operating time are presented in Figures 1–3. It follows from the analysis of structure of metal of all blades that as a result of long-term service at operating temperatures the structure-phase state of material changes considerably and is deteriorated. Trans- and intercrystalline microcracks in the structure were not revealed, but microstructure of alloy is characterized by difference in grains. It is known that at the boundaries of different-grain metal in the process of service the cracks can appear as the volumes of coarse and fine grain deform in different way. Metal in the root part has more homogeneous microstructure. In the metal with lower operating time (53,000 h) the strengthening intermetallic γ'-phase (Ni_3Al, Ti) is almost completely dissolved in the solid solution and its remnants have chaotic distribution in the volume of grains. The grain boundaries are linear, filled with fine-dispersed carbide and intermetallic phases (see Figure 1).

With increase of service time up to 60,142 h, the precipitation of large carbides (up to 3 μm), forming in chains along the grain boundaries, is observed in microstructure of specimens (see Figure 2). The redistribution of strengthening intermetallic phase was occurred, the larger part of which was precipitated near grain boundaries which depletes the body of a grain. With increase of service time of material up to 62,449 h (see Figure 3) the additional precipitation and coarsening of carbides of the type MeC, MeC_6, MeC_{23} of dispersion from 0.5 to 6.0 μm and precipitation of a large amount of fine-dispersed γ'-phase (Ni_3Al, Ti) occur. According to the instruction on prolongation of service period of metal of base ele-

Table 1. Mechanical properties of alloy KhN65VMTYu

State of material	σ_t, MPa	$\sigma_{0.2}$, MPa	δ, %	ψ, %
TU 108.02.005–76	≥ 850	490–660	≥ 20	≥ 25
After service during 53,000 h	990	340	19	22
	1030	445	26	23
After service during 60,142 h	1090	430	22	28
After service during 62,449 h	1000	350	21	26
RHT modes: 1. Hardening from 1160 °C for 2 h, air cooling + ageing at 1000 °C for 4 h, air cooling + ageing at 900 °C for 8 h, air cooling + ageing up to 820 °C for 15 h, air cooling	770	350	44	41
2. Hardening from 1160 °C for 2 h, air cooling + ageing at 950 °C for 6 h, air cooling + + ageing up to 820 °C for 12 h, air cooling	680	410	22	22
3. Hardening from 1160 °C for 2 h, air cooling + ageing at 800 °C for 12 h, air cooling	790	415	42	39
4. Hardening from 1050 °C for 3 h, air cooling + ageing at 850 °C for 12 h, air cooling	920	490	36	25
5. Hardening from 1150 °C for 3 h, air cooling + ageing at 850 °C for 12 h, air cooling + ageing at 750 °C for 24 h, air cooling	980	460	30	26
Service for 60,142 h + RHT	990	555	28	43
Service for 62,449 h + RHT	940	485	20	24

ments of turbines SO 153-34.17.448–2003 the conglomerates of chromium carbides of the size of more than 5 μm are not admitted in microstructure of alloy KhN65VMTYu. The alloy with operating time of more than 62,000 h cannot be more under the service.

As a result of microspectral analysis of carbide inclusions located at the boundary and inside the grains of metal, the spectrograms were obtained which allow us to state that the investigated carbide inclusion, presented in Figure 4, *a*, was formed on the basis of tungsten, molybdenum and chromium and corresponds to complex carbide of group II of the type (W, Mo, Cr)C, while in Figure 4, *b* — to carbide of molybdenum Mo_2C, which is also carbide of the group II (interstitial phase). Due to a low carbon content in the alloy KhN65VMTYu (≤0.07 %) the amount of carbide phase in it is negligible and it is located mostly along the boundaries of austenite grains.

The results of mechanical tensile tests of specimens at room temperature showed that the material in post-service state does not correspond to the requirements of TU 108.02.005–76 as to yield strength and ductility properties independently of the period of operating time. It is seen from Table 1 that in the process of long service the increase of strength and decrease of ductile properties occurred in material of blade airfoil as a result of additional formation of disperse particles of γ′-phase. Tensile strength of material increased up to 1000–1090 MPa at 850 MPa admissible according to TU 108.02.005–76, and yield strength decreased down to 340–430 MPa at the standard of 490–660 MPa.

The testing of alloy KhN65VMTYu on the material with the lowest operating time (53,000 h) of experimental conditions of reduction heat treatment (RHT) resulted in the decrease of level of strength and considerable increase of ductile properties (elongation and reduction in area). The optimal result was obtained after application of the conditions 4 and 5 of RHT (see Table 1). It follows from the analysis of microphotos in Figure 5 that microstructure of alloy KhN65VMTYu becomes more homogeneous, the decrease in grain difference occurs. RHT results in some stabilization of microstructure, increase of amount of

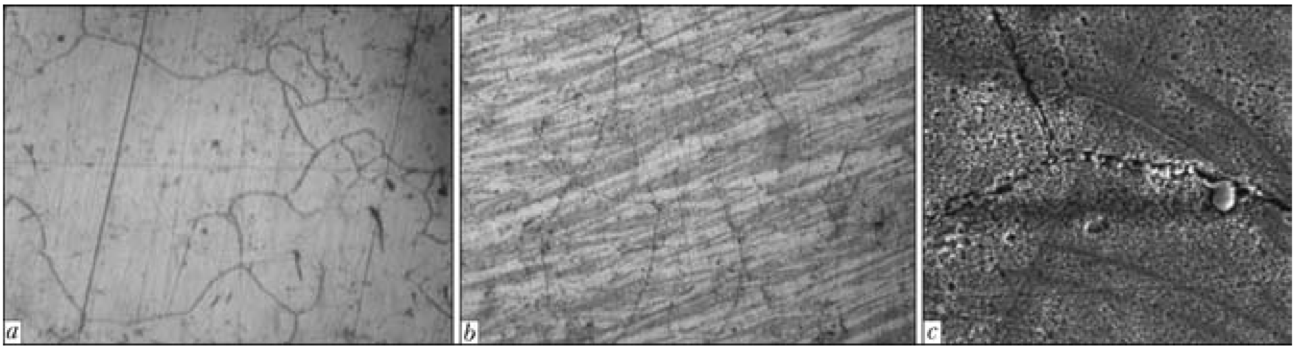

Figure 1. Microstructure of alloy the KhN65VMTYu specimens after service during 53000 h cut from the first (*a*, *b* — ×250) and root part of blade (*c* — ×10000)

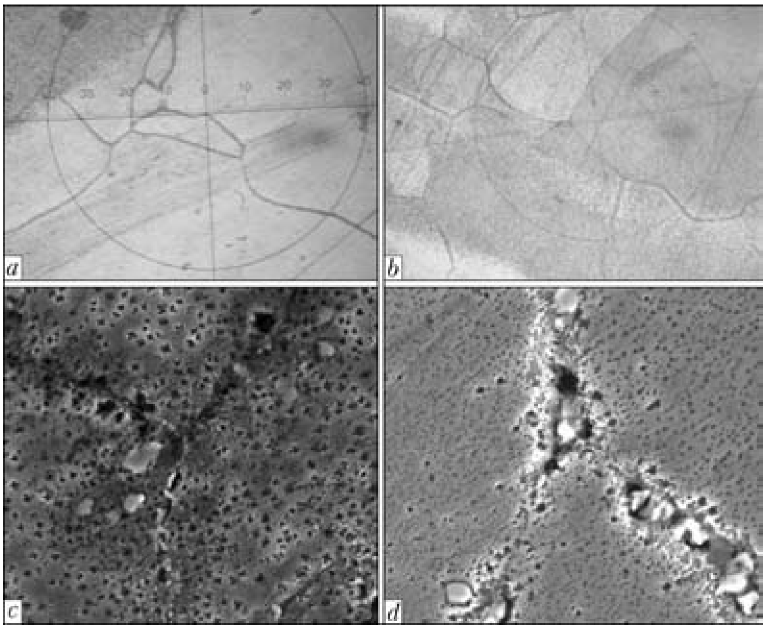

Figure 2. Microstructures of the alloy KhN65VMTYu specimens after service during 60,142 h cut from the first (*a*, *c*) and root part of blade (*b*, *d*) (*a*, *b* — ×250; *c*, *d* — ×10000)

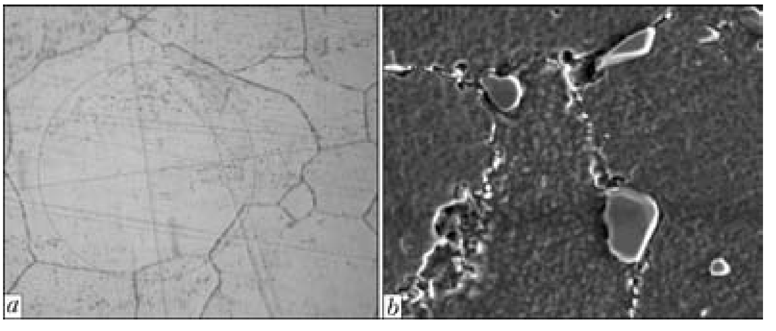

Figure 3. Microstructure of alloy KhN65VMTYu after service during 62,449 h (*a* — ×250; *b* — ×1000)

γ′-phase: in use of step conditions of RHT the content of γ′-phase is increased up to 3–4 %, during one-step ageing at 820 or 850 °C the amount of γ′-phase is increased up to 10 %, which is the admissible content for this alloy. In RHT of specimens using the condition 5 during 30 h, the complete regeneration of degrade structure of blade metal occurs. In this case the excessive intermetallic γ′-phase is observed in a form of fine-disperse precipitates. The content of γ′-phase after RHT is increased up to 12 %, however at long-time ageing the precipitation of coarse carbides at the grain boundary occurs which are the concentrators of stresses.

For the alloys with operating time of 60,142 and 62,449 h, the condition 4 of RHT was applied (see Table 1), which showed optimal values of structural and mechanical values on the specimens of alloy with operating time of 53,000 h.

Table 2. Data of X-ray diffraction analysis of materials

State of material	D, nm	ε	r_L, cm^{-2}	ρ_ε, cm^{-2}
After service	270	0.0004	$4.1\cdot10^9$	$8\cdot10^9$
Surfacing using wire 04KhN50VMTYuB-VI	57	0.00011	$9.2\cdot10^{10}$	$6.1\cdot10^8$
After surfacing and tempering	~500	0.00046	~10^9	10^{10}

In RHT on the alloys with operating time of 60,142 and 62,449 h (Figure 6) the satisfactory result was obtained: the dissolution and redistribution of intermetallic phase and refining of carbides occurred. The changes in microstructure were positively reflected on mechanical characteristics of material presented in Table 1. RHT resulted in decrease of tensile strength to 990–940 MPa and increase of yield strength up to 555–485 MPa which corresponds to the standardized values of mechanical properties.

To restore geometric sizes of blades the welding-surfacing works were applied using wire on nickel bases of grade 04KhN50VMTYuB-VI (EP648-VI) of the following chemical composition, %: 0.04 C; 0.14 Mn; 0.25 Si; 22.2 Cr; 66.3 Ni; 1.26 Nb; 2.4 Mo; 1.6 Ti; 0.4 Al; 0.95 Fe; 4.4 W. The values of strength characteristics of selected surfacing wire are close to the values of base metal of blades (as to tensile strength σ_t = 800 MPa $K = 0.94\sigma_t^{BM}$, as to yield strength $\sigma_{0.2}$ = 470 MPa $K = 0.95\sigma_y^{BM}$) which satisfies the requirements for the deposited material. To relieve residual stresses after welding, the tempering at 700 °C

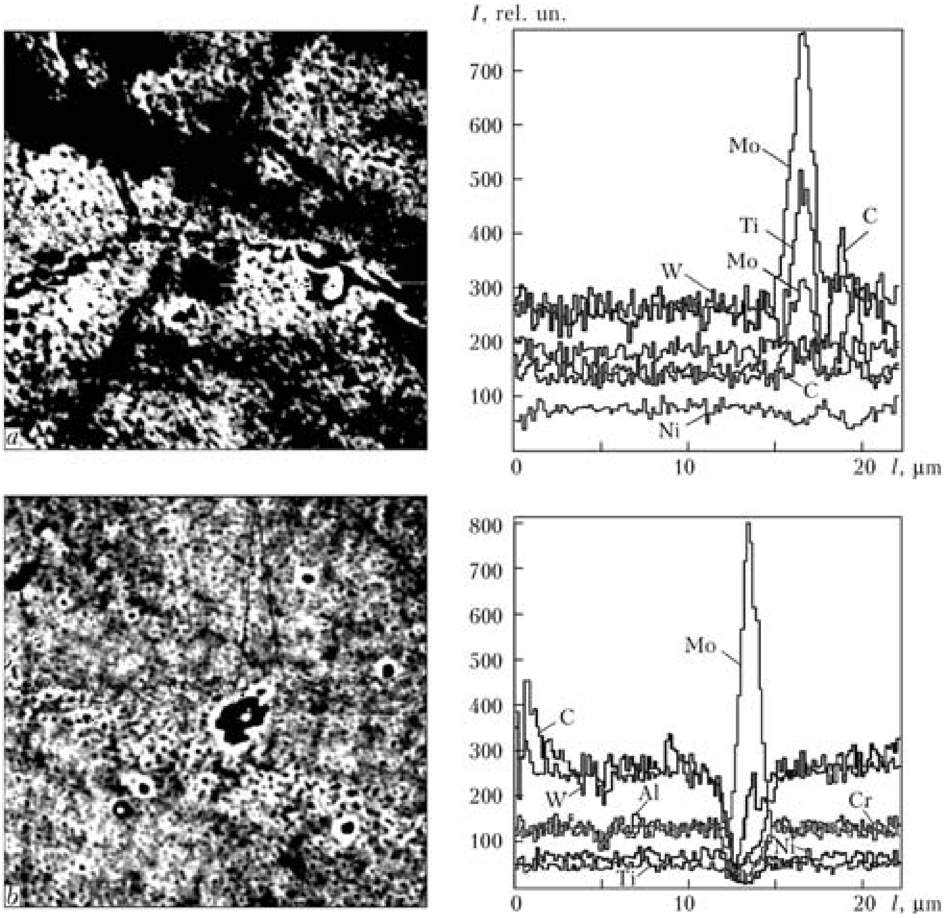

Figure 4. Microstructures and spectrograms of carbide inclusions detected at the surface of cross sections: *a* — after service; *b* — after RHT using mode 4 (see Table 1)

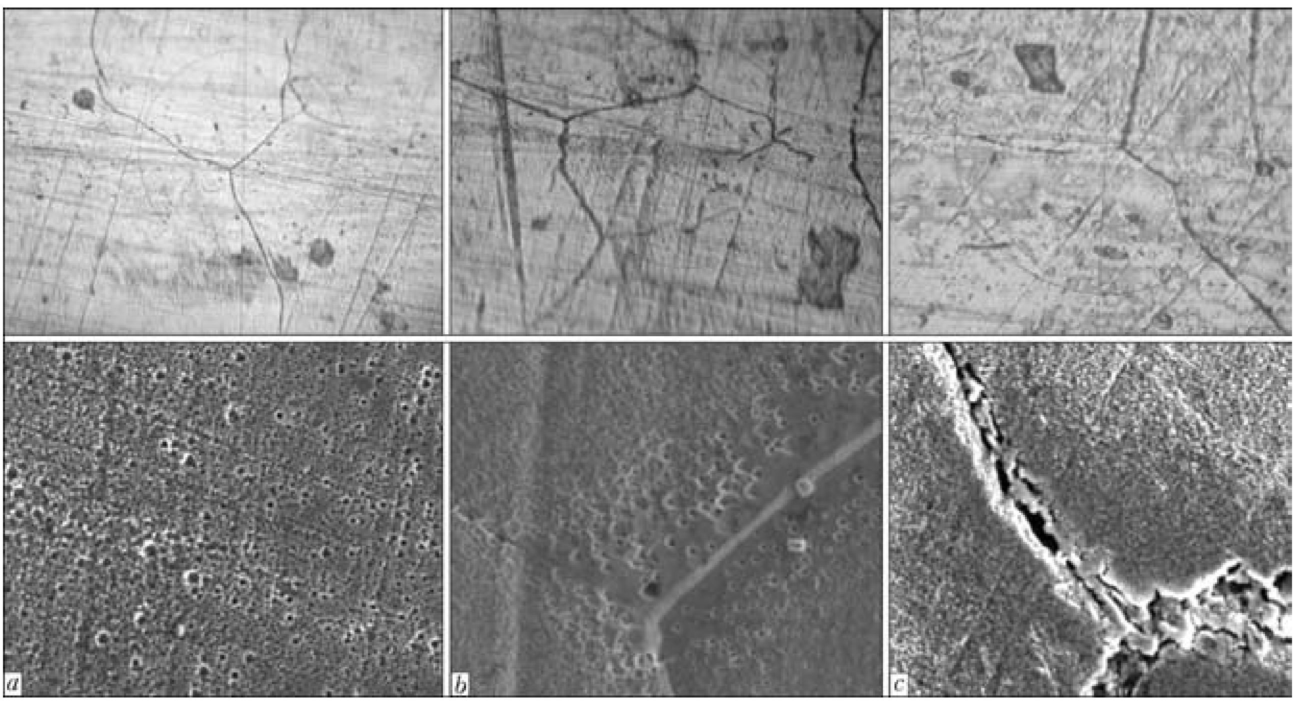

Figure 5. Microstructure of alloy KhN65VMTYu with operating time of 53,000 h after different variants of RHT: *a* — mode 1; *b* — mode 2; *c* — mode 5 (see Table 1)

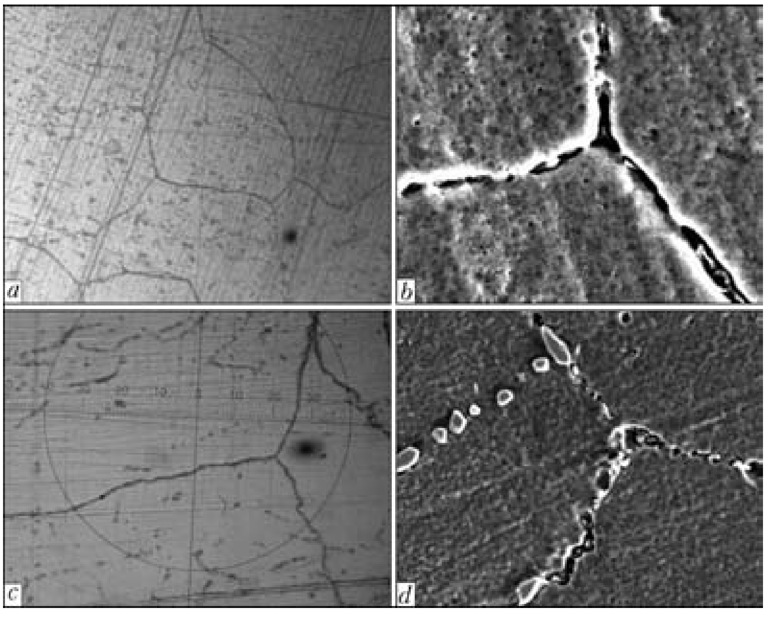

Figure 6. Microstructure of alloy KhN65VMTYu after RHT: *a*, *b* — mode 4 at operating time of 60,142 h; *c*, *d* — the same at operating time of 62,449 h (*a*, *c* — ×500; *b*, *d* — × 10000)

for 8 h was done. Table 2 gives results of X-ray diffraction analysis of specimens.

In the post service state the average level of microdeformations and homogeneous distribution of density of dislocations inside and at the boundaries of subgrain blocks were recorded in the blade material. The surfacing considerably refines subgrains and abruptly increases the density of boundary dislocations (almost by 2 orders), that in its turn can embrittle the boundaries. RHT facilitates the coarsening of blocks of mosaics and decreasing the density of dislocation defects at the boundary.

On the basis of carried out research works one can conclude that material of blades with different operating time from 53,000 to 62,449 h has a degrade microstructure and needs RHT. The operation of blades of alloy KhN65VMTYu for more than 62,000 h without restoration repair is not desirable as the negative changes in microstructure (formation of coarse carbides at the boundaries of grains) can result in fracture of blades. All the blades investigated in this work are maintainable and have passed the complete restoration cycle including heat treatment for reduction of structure and physical-mechanical properties, surfacing works for restoration of geometric sizes of a workpiece and deposition of protective heat-resistant coating using gas-plasma method. At the present time the blades are installed into the units and are in service. Thus, technological cycle of reduction treatment can be presented in a form of scheme:

100 % incoming control + RHT (hardening + ageing) + machining (defects preparation) + surfacing works (restoration of geometry), control + heat treatment (tempering for stress relieving) + preparation of surface for coating + deposition of protective heat-resistant coatings using gas-plasma method (Ni–Al + + ZrO_2) + 100 % outgoing control.

From the editorial board. In the opinion of the reviewer of this work, the performance of heat treatment of as-serviced blades in air at 1050 °C can result in oxidation of surface of a root, and further cleaning or grinding does not eliminate thinning of the root part and not air-tight joining of blades.

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