UDK 669.1:621.438:620.18
Pregledni članek/Review article

ISSN 1580-2949
MTAEC9, 43(6)277(2009)

OPERATION MIKROSTRUCTURE AND LIFETIME OF GAS TURBINE ENGINE (GTE) COMPONENTS

DELOVNA MIKROSTRUKTURA IN TRAJNOSTNA DOBA SESTAVNIH DELOV PLINSKIH TURBIN (GTE)

Leonid B. Getsov[1], G. P. Okatova[2], A. I. Rybnikov[3], D. G. Fedorchenko[4]
[1]State Polytechnic University, SPb; Zakevskii pr. 43 appt. 89, 195213 Russia, St. Petersburg
[2]Byelorussian Scientific & Research Institute of Powder Metallurgy
[3]NPO CKTI
[4]Energomash Corporation
guetsov@yahoo.com

Prejem rokopisa – received: 2008-11-15; sprejem za objavo – accepted for publication: 2009-06-04

Changes of microstructure and mechanical properties of stels and alloys and protection coatings decreasing the serviceability of components after long time use in gas turbine engines are described. Different examples of damage on turbine blades are shown. Methods for the evaluation of residual life of components are suggested. For a large series of metals and alloys, the high temperature properties after annealing up to 40 000 in temperature range 550 °C to 900 °C and are given, also.

Key words: gas turbine components, steels and alloys, changes of microstructure and properties, method of evaluation of serviceability

Opisane so spremembe mikrostrukture in mehanskih lastnosti jekel in zlitin ter varovalnih prevlek, ki zmanjšajo trajnostno dobo sestavnih delov plinskih turbin. Prikazani so različni primeri poškodb lopatic teh turbin. Predlagane so metode za oceno preostale trajnostne dobe sestavnih delov. Za precejšnje število jekel in zlitin so navedene mehanske lastnosti pri visokih temperaturah do 40 000 h žarjenja v razponu temperatur med 550 °C in 900 °C.

Ključne besede: sestavni deli plinskih turbin, jekla in zlitine, sprememba mikrostrukture in lastnosti, metode za oceno preostale trajnostne dobe

1 INTRODUCTION

For the manufacture of components for gas turbines a great variety of special steels and alloys are used because of the continuously increasing operating temperature. This led to the situation of components and materials in use in various GT units with serviceability not suited sufficiently for the operating temperature and time. Therefore, the acquisition of data on the microstructural state of GTE components from such materials may indicate to operationl damages and highlight the potential of the prolongation of their lifetime.

2 MATERIAL MICROSTRUCTURE AND CONTINUOUS OPERATION BEHAVIOR

The serviceability features related to the operating times at elevated temperatures include [1]:

1. Needle-like topological close-packed phases (σ and μ) appearing in the Ni-based high-temperature alloys microstructures may degrade the ductility and long-term strength causing possibly, also, non expected changes of high-temperature strength and low-cycle fatigue resistance.

2. A des-alloyed layer formed at the surface of high-temperature alloys may lower the long-term strength, low-cycle fatigue and thermal fatigue resistance, while the change of composition and thickness of the coating layer due to the diffusion redistribution of elements with the parent metals may degrade significantly the protective capability of the coating.

3. The decrease of grain size in austenitic steels and Ni-alloys indicates to the progressing of recrystallization, while, grain size coarsening indicates to a significant increase of temperature.

4. Creep pores along the grain boundaries testify for a considerable material degradation, particularly the lowering of ductility.

5. The decrease of the share of γ'–phase and it coarsening at continuous operation is sign of softening of Ni-based high-temperature alloys caused by high temperatures. The increase of the share of finely dispersed γ'-phase indidates either to a long-time exposure of the alloy to low temperatures that may cause embrittlement, or to a considerable overheating with γ'-phase dissolution and precipitation at cooling as fine dispersion (**Figure 1**).

6. With increased presence of a second-phase at grain boundaries, the alloy ductility is diminished.

7. The recrystallization at the surface of single-crystal blades, irrespective of its reason (manufacture, operation, coating application), degrades the long-term strength and thermal fatigue resistance of blades.

A careful metallographic examination may discover microcracks of different origin appeared in the manu-

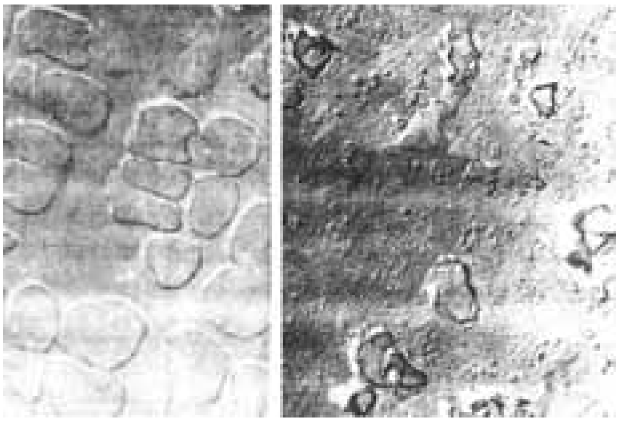

Figure1: Microstructure of a blade overheated in operation
Slika 1: Mikrostruktura lopatice, ki je bila pregreta pri uporabi

facturing of the alloy, the manufacturing of components, GTE testing and GTE operation. Micro-cracks impair the alloy properties, affect its serviceability and can, in certain conditions, grow in size at static and at low-cycle stressing creep and at vibratory stressing.

3 EFFECT OF CONTINUOUS OPERATION ON MATERIAL PROPERTIES

Long-term exposure of a material to elevated temperatures can significantly affect its serviceability. Relationships have been proposed that connect the mechanical properties with the operating conditions[5]. Extending the concept of the creep equation with Rabotnov's structural parameters s_i.

$$p^{\bullet} = F(s_1(\tau,T),\ s_2(\tau,T),\ s_3(\tau,T),\ .....\ T,\sigma) \qquad (1)$$

to other material properties the relationships have been proposed:

$$\sigma_B = F(s_1(\tau,T),\ s_2(\tau,T),\ s_3(\tau,T),\ ....T,v) \qquad (2)$$

$$\sigma_{0,2} = F(s_1(\tau,T),\ s_2(\tau,T),\ s_3(\tau,T),\ ....T,\ v) \qquad (3)$$

$$\sigma_{\mathrm{lts.}} = F(s_1(\tau,T),\ s_2(\tau,T),\ s_3(\tau,T),\ ...\ T,t) \qquad (4)$$

$$\delta = F(s_1(\tau,T),\ s_2(\tau,T),\ s_3(\tau,T),\ ...\ T,v) \qquad (5)$$

$$\Delta\varepsilon = F(\mathrm{s}_1(\tau,T),\ s_2(\tau,T),\ s_3(\tau,T),\ ...\ T_{\max},\ T_{\min},\ N,\ \tau_c) \qquad (6)$$

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

$$\mathrm{d}l/\mathrm{d}\tau = F(s_1(\tau,T),\ s_2(\tau,T),\ s_3(\tau,T),\ ...\ T,K_1) \qquad (8)$$

With: v – deformation rate, τ_c, $T_{\max}$, $T_{\min}$, N – respectively, cycle period, maximal and minimal cycle temperature, number of cycles to the initiation of thermal fatigue cracks for thermal cyclic loading, K_1 – stress intensity factor. Note that, unlike[1] this article is aimed to define the criteria characterizing the microstructural state, thus, to impart a physical meaning to the microstructural parameters $\boldsymbol{s_1(\tau,T)}$, $\boldsymbol{s_2(\tau,T)}$, $\boldsymbol{s_3(\tau,\ T)}$, ...

To estimate the stress-strain state and safety margins for the components of a definite alloy allowing for changes of microstructure, it is necessary to know the kinetics of change of yield strength $\boldsymbol{\sigma_{0,2}}$, elongation δ, creep rate $\boldsymbol{p^{\bullet}}$, creep cracks growth rate $\mathbf{d}\boldsymbol{l}\mathbf{/d}$, cyclic deformation strength $\boldsymbol{S_{0,4}}$, thermal fatigue $\Delta\varepsilon$ and long-term strength $\boldsymbol{\sigma_{\mathrm{lts}}}$. after long time high temperature exposure of the component.

Tables 1–5 show the mechanical properties and long-term strength tested on a number of steels and alloys applied in GT units in continuous operation[5].

It is possible to derive digitally a discrete form for the equations (2) to (8) applying the data given in the tables.

4 CONCEPT OF LIFETIME PROLONGATION FOR GTE COMPONENTS

To estimate the quality of the microstructure of components after long time operation, which is the basis of a reliable prediction fof lifetime prolongation, different methods may be applied[2,3,4], metallographic examination with the replication method, X-ray inspection

Table 1: Effect of long time exposure on mechanical properties of steels and alloys
Tabela 1: Vpliv dolgotrajnega zadržanja na mehanske lastnosti jekel in zlitin

Material	Anneling Conditions		Test Conditions		Time to Fracture, t_f/h	Elongation
	T/°C	Time, t/h	T_t/°C	σ/MPa		δ/%
EI481 (37Х12Н7Г8МФБ)	650	0	650	270	1000	4.14
		40000			72	30
EP126 (ХН28ВМАБ)	800	0	900	50	242	18
		5000			65	45
EI787 (ХН35ВТЮ)	650	0	650	380*	1350	-
		10000			148	-
		0	650	350	8000	1,6
		50000			442	15
EP99 (ХН50МВКТЮР)	800	0	800	200	374	24
		5000			193	20.4
EP126 (ХН28ВМАБ)	800	0	800	100	684	28.8
		5000			151	10
	800	0	900	50	242	18
		5000			65	45

Table 2: Effect of long time exposure on mechanical properties of Ni-based steels and alloys
Tabela 2: Vpliv dolgotrajnega zadržanja na mehanske lastnosti nikljevih jekel in zlitin

Alloy	Aging Temperature, T_a/°C	Aging Time, t_a/h	Test Temperature, T_t/°C	$\sigma_{0,2}$/ Mpa	σ_b/MPa	δ/%	Ψ/%
EP99	Initial		20	815	1170	50.2	–
	750	5000		610	900	57	–
	800	2000		982	1040	0.5	–
		5000		848	1230	5.0	–
	900	2000		858	990	1.0	–
		10000		502	765	4.7	–
GS6U	Initial	–		760–850	770–900	5.9–27.8	12–28
	800	2000		880	1030	1.2	–
		5000		853	862	12.7	–
	850	2000		710–900	880–910	1.5	7.0
		5000		820	1040	5.9	5.9
	900	2000		678	832	11.1	12.6
EP220	Initial	–	800	771	1008	6.5	10.8
	800	16000		816	892	1?9	6,5
EI929 (XH55BMTKЮ)	550	10000	20	777	1170	18	18
	600	10000		780	1160	15	17
	650	10000		810	1130	11.5	11.5
	700	10000		750	1200	17	16
	750	10000		690	1220	23	22
	800	10000		630	1030	15	15
EI893Л	Initial	–		513	734	23.5	22
	700	5000		578	817	13.1	18,2
	750	5000		470	757	16.2	22.7
	800	5000		442	706	16.1	19.1
EP126	Initial	–		468	890	41	–
	750	10000		479	819	3.9	–
	800	10000		446	872	14.2	–
	900	10000		364	814	24.4	–
EI703 (XH38T)	Initial	–		460	808	40.3	–
	750	10000		338	713	19.8	–
	800	10000		313	709	30.2	–
	900	5000		165	550	44	
CNK–7 RS	700	3000	20	864–975	880–1007	0.8–3.9	0.7–7.5
			700	847	1082	7	14.4
	750	3000	20	838	888	1.7	7.9
			750	793–826	931–1021	3.2–5.0	6.2–10
	800	3000	20	718–753	791–867	1.9–4.5	6.2–12.9
			800	690–753	796–862	6.1–10.8	9.7–24.9
	850	3000	20	672–772	779–833	2.3–5.1	2.2–12
			850	584–650	690–760	3.1–13.1	8.4–24.9
ZMI–3	650	5000	20	845–877	909–944	1.8–1.5	8.1
			650	817	976	3.7	
	700	3000	20	842–917	934–972	1.8–4.1	3.6–4.0
			700	891–905	1050	4.0–6.4	4.0–8.2
	750	3000	20	807	874	2.0	4.9
			750	745	947	12.4	18.7
	800	3000	20	701–848	764–948	1.4–5.0	2.7–7.0
			800	649–848	745–948	4.0–12.0	6.2–19.7
	850	3000	20	617–772	724–859	2.9–4.0	4.6–5.0
			850	460–690	626–820	3.7–13.6	5.2–22.0
GS6K	600	10000	20	1000–1100	1070	2.1	4.6–5.6
			600	1000	1080	2.2	5.6
	650	10000	20	1040	1080	2.9	4.3–5.3
			650	990	1060	1.6	3.0
	700	10000	20	1000	1020	1.5–1.7	1.4–1.6
			700	1000	1060	0.8	0.9
	800	10000	20	830	950	1.6	2.0
			800	820	950	2.2	4.3
	850	10000	20	730–780	920–890	2.5–3.5	5.0–5.6
			850	710	810	1.7	2,1
	900	10000	20	680	840–890	3.0–4,3	5.5–6.5
			900	620	670	2.2	2,0
	950	10000	20	630	800–870	3.0–3.5	4.5–8.2
			950	500	560	5.4	7.5
	1000	1000	20	740	860–900	2.3–2.5	2.8–4.8
EI481	Initial	–	20	733–806	1054–1068	17.8–23.7	24.5–43.2
			650	497–506	599–614	14.3–14.7	45.0
	550	10000	20	772–792	103–106	18.4–22.2	28.4–40.7
			650	557–595	620–658	9–10	35.2–35.5
	600	10000	20	613–622	964–955	20.6–24.2	28.9–29.9
			650	422–437	540	15.0–15.5	41–43.2
	650	10000	20	415	813	24.8	29.2
			650	328	453	18.5	39.5

Table 3: Effect of long time exposure on plasto-elastic deformation strength for pearlitic and martensitic steels ($\sigma_{0.2\ \mathrm{aged}}/\sigma_{0,2\mathrm{init}}$) at 20 °C
Tabela 3: Vpliv dolgotrajnega zadržanja na plasto-elastično deformacijsko trdnost perlitnih in martenzitnih jekel ($\sigma_{0.2\ \mathrm{aged}}/\sigma_{0,2\mathrm{init}}$) pri 20 °C

Aging Temperature, T_a/°C	Aging Time, t_a/h	15XMΦ	EI802 (15X12BHMΦ)	EP752	EP291	15X11MΦ	20X13
500	40000	0.88					
550	5000		0.92				
550	10000						0.86
600	5000		0.89		0.92		
600	10000					0.78	0.75
600	30000	0.78					
620	2500			0.84			
650	2500			0.78			
650	5000				0.86		
650	10000				0.82		

Table 4: Effect of long time exposure on plastoe-elastic deformation strength for austenitic steels ($\sigma_{0.2\ \mathrm{aged}}/\sigma_{0,2\mathrm{init}}$) at 20 °C
Tabela 4: Vpliv dolgotrajnega zadržanja na plasto-elastično deformacijsko trdnost avstenitnih jekel ($\sigma_{0.2\ \mathrm{aged}}/\sigma_{0,2\mathrm{init}}$) pri 20 °C

Aging Temperature, T_a/°C	Aging Time, t_a/h	20X23H18	EI572	EI481	EI787	EI703
600	5000		1	1	1,2	
650	10000	1.13	-	0.83	0.94	
	20000		1	0.87		
	30000				0.91	
700	5000		0.79	0.7		
	10000	1.1				
750	5000	1	0.75			0.8

Table 5: Effect of long time exposure on plasto-elastic deformation strength for Ni-based alloys ($\sigma_{0.2\ \mathrm{aged}}/\sigma_{0,2\mathrm{init}}$) at 20 °C.
Tabela 5: Vpliv dolgotrajnega zadržanja na plasto-elastično deformacijsko trdnost nikljevih zlitin ($\sigma_{0.2\ \mathrm{aged}}/\sigma_{0,2\mathrm{init}}$) pri 20 °C

Aging Temp., T_a/°C	Aging Time, t_a/h	EI868	EP99	EP220	EI607	VG85	EI867	EI437B
700	10000				0.69		0.89	
750	500	1	-	-	-	-	-	1.36
	1000	1	-	-	-	1.03	-	-
	5000	0.9	-	-	-	1.07	-	-
	10000	0.83	-	-	-	-	-	-
800	2000	0.9	1.2	0.9	-	1.03	-	-
	5000	0.87	1.04	0.83	-	0.95	-	-
	16000	0.77	-	0.9	-	-	-	—
900	1000	0.75	-	-	-	1	0.82	-
	2000	0.78	1.05	0.93		0.82		
	5000	0.78	-	0.85	-	0.59	-	-
	10000	0.68	0.62	-	-	-	-	-

with phase analysis, X-ray spectral micro-analysis, etc. and appying interrelation of microstructure and properties. The quality criteria for microstructure and it distribution all over the component body should be established up for each material considering the stressing and stress distribution of the GTE component considered.

Based on the all-inclusive study of the interrelation between residual endurance and some microstructural features emerging in the metal as result of its damage, the blades of engines run at different operating and climatic conditions[1,6,7,8,9] can be examined and the effect of operating rate on damage rate increase estimated. The base for decision is the comparison with the initial microstructure. For the indirect evaluation of the quality of the surface layer, it is advisable to measure its hardness and micro-hardness.

With turbine blades as example, in the scheme of the methodology for predicting the residual capacity of GTE high-temperature components after long time operation is shown in **Figure 2**.

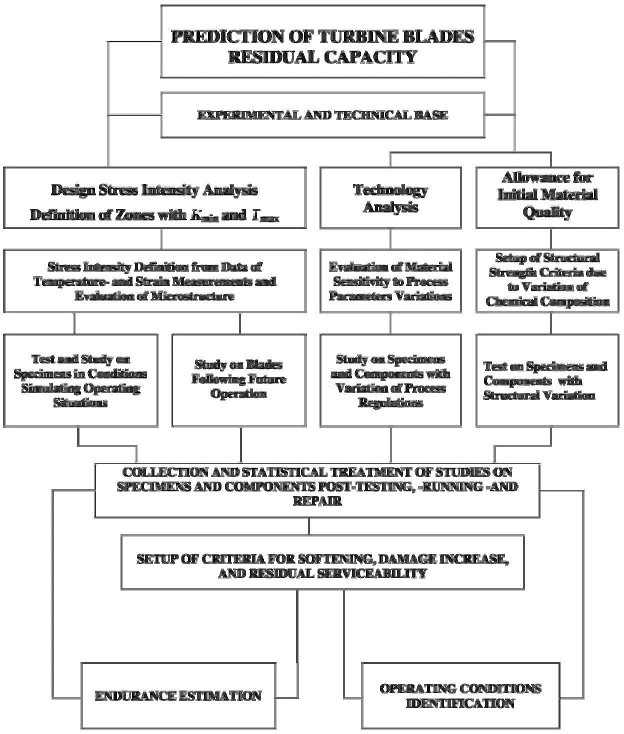

Figure2: Methodology for predicting the residual capacity of turbine blades (K_{min} is the minimal safety margin value all over the blade)

Slika 2: Metodologija za napovedovanje rezidualne uporabnosti turbinskih lopatic (K_{min} je vrednost minimalnega varnostnega razpona na celi lopatici)

5 COATING QUALITY CRITERIA

The reliability of the prediction of the residual service life of coated parts depends largely on the state of the coating[1,10]. After long time the coating quality use depends on its type: diffusion, condensation, metallic, metallic with an outer ceramic layer. As a rule, the quality of the coating after use is evaluated in comparison with its initial quality. In this case, the quality criteria for diffusion and metal condensation coatings after long use are: layer thickness uniformity, absence of chipping and coating layer peeling, absence of cracks, especially thermal fatigue cracks (**Figure 3**), of significant surface oxidation (**Figure 4**) and pit-type corrosion damage, absence of significant redistribution of the basic alloying elements of the coating (Al, Cr) and significant changes in phase composition of the coating.

The impoverishment of a diffusion coating with aluminum and chrome reduces sharply it protective properties and, as with pits formation, leads to the decrease of service life. The methods of calculated prediction of the diffusion redistribution of coating elements were examined in[1]. As criterion of serviceability of diffusion coatings the decrease of surface concentration of the element determining the protection against corrosion by up to one third of the difference between the initial concentration in the coating and in

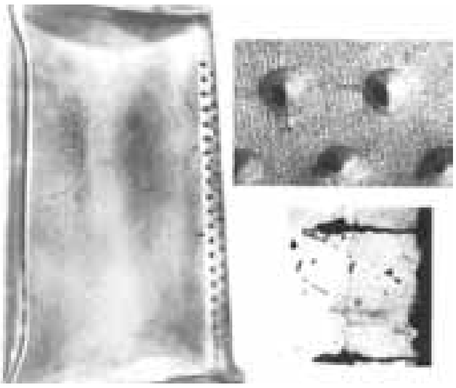

Figure3: Appearance of burning-out thermal fatigue cracks in the basic material of the edge of a turbine blade of ŽS6 alloy with NiCrAlY coating

Slika 3: Videz odžganih termičnih razpok v materialu roba lopatice iz zlitine ŽS6 s pokrivno plastjo NiCrAlY

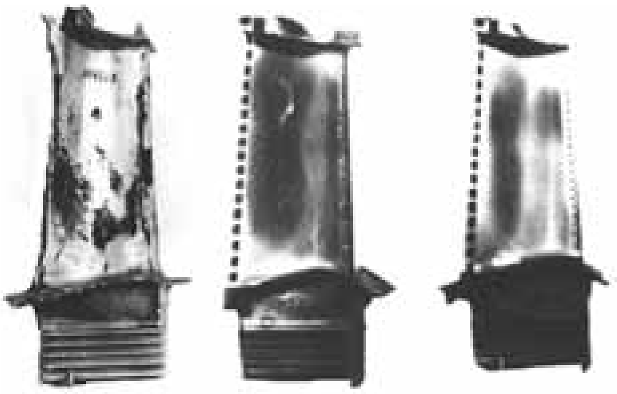

Figure 4: Turbine blades without (a) and with a thermal-barrier ceramic coating (b, c) after comparison tests in an impeller of an aircraft gas-turbine engine: b – view of the blade before carbon deposit removal, c – view of the blade after carbon deposit removal

Slika 4: Turbinske lopatice brez (a) keramične pokrivne plasti in z njo (b, c) po primerjalnih preizkusih v impellerju letalske plinske turbine; b- videz lopatice pred odstranitvijo depozita ogljika, c – vodez lopatice po odstranitvi depozita ogljika

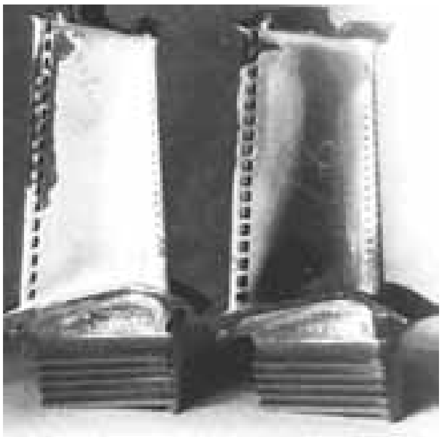

Figure 5: Peeling of the ceramic layer of the thermal protection coating of a turbine blade after the expiration of its operating time in the engine

Slika 5: Luščenje varovalne keramične prevleke po preteku dobe uporabnosti v motorju

Figure 6: Cracks in and below the ceramic layer. Cracking and peeling of the ceramic layer of the blade in the process of operation
Slika 6: Razpoke v in keramični prevleki in pod njo. Razpokanje in luščenje keramične prevleke med uporabo

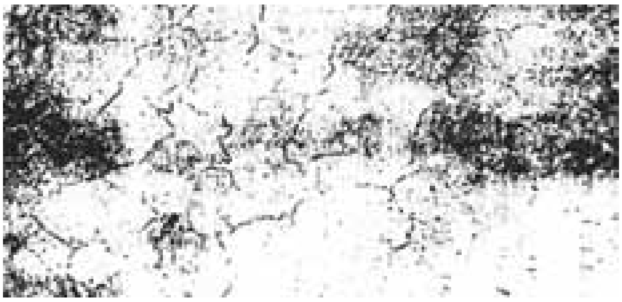

Figure 7: Fragmentation of the thermal protection ceramic coating
Slika 7: Fragmentacija keramične varovalne plasti

the basic metal can be used. Coating corrosion damage with depth up to 2/3 of the layer thickness can be used as second criterion.

For ceramic coating layers, the criteria of quality are: porosity (density), uniformity of layer thickness, thickness of the interlayer Al_2O_3 on the side of the metallic layer and, most importantly, the presence of chipping, cracking and peeling (**Figures 5 and 6**). On the contrary, the fragmentation of the thermal protection coating layer (**Figure 7**) increases the resistance to cracking and peeling and is not a defect.

6 CONCLUSION

The investigations of changes of microstructure and mechanical characteristics of materials and coatings after long use enable to solve, on scientifical base, questions connected with the possibility of increasing the service life of parts. Knowing the dependence of properties and microstructure of materials, it is possible to evaluate the change of initial properties with examination of the microstructure and predict the residual service life. The data for a number of materials cited in this report can serve as the basis for such predictions.

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