Mechanisms of Operating Property Alterations of $\alpha+\beta$-Titanium Alloy Blades Modified by Intense Pulsed Electron Beams

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Abstract – The present report reviews the results of investigations dedicated by the application of intense pulsed electron beams for surface processing of titanium alloy compressor blades of aircraft engines. The irradiation of these components was carried out at GESA-1 and GESA-2 accelerators under the following conditions: electron energy – E=115–120 keV; pulse duration – τ=20–40 μs; and the energy density in a pulse (w) as well as the number of pulses (n) were varied from w=16 J/cm^2, n=1 up to w=90 J/cm^2, n=10. The results of investigating the irradiated blades, which were obtained using EAS, X-ray analysis, SEM and TEM methods, were discussed. It is shown that IPEB treatment at low values of the energy density induces rapid melting, ablation and solidification leading to the formation of non-equilibrium microstructures. In this case the irradiation (w=18–20 J/cm^2) leads to surface smoothing, rapid solidification of the material in the surface layer with thickness near 20–25 μm. As a result, surface roughness of the blades can be decreased. In this case the most important operating characteristics of compressor blades were improved cardinally by irradiation with intense pulsed electron beams. The mechanisms of operating property alterations of $\alpha+\beta$ – titanium alloy blades modified by intense pulsed electron beams are discussed.

1. Introduction

The first investigations, dedicated to the industrial application of the intense pulsed electron beams (IPEB) for property modification of metals and alloys were began more 20 years ago by Prof. D. Proskurovsky (Institute of High Current Electronics, Tomsk) and Prof. V. Engelko (Efremov Institute of Electro-Physical Apparatus, Sankt-Petersburg). The results of these studies, carried out with the use of samples from martensit, ferrit and austenit steels, give a possibility to make the conclusion on high effectivness of IPEB application for improvement of such properties as friction, wear, corrosion resistance, creep, strength etc. At the present time there are many already published data about the effect of the irradiating conditions by IPEB on the physical and chemical state of material surface layer parts produced of steels, nickel and zirconium alloys, composit and organic materials etc.

The objective of the present paper is the analysis of the experimental results obtained by authors and dedicated to study of the physical and chemical state of the part surface layer from $\alpha+\beta$-titanium alloys and determination of their service properties before and after irradiation by IPEB.

2. Experimental

The patterns and gas turbine engine compressor blades (Fig. 1) from $\alpha+\beta$-titanium alloys (VT6, VT8 and VT9), composition of which are given by V. Solonina etc. [1], were used as the study and test objects. The IPEB irradiation was performed at the GESA-1 and GESA-2 accelerators with the energy density change in a pulse from 16–18 to 80–90 J/cm^2 and the the pulse number from 3 to 10. The irradiation conditions were as follows: electron energy of E=115–120 keV, pulse duration of τ=20–40 μs, beam cross-section area of S=30–80 cm^2, heterogeneity of energy density distribution of 10 %. After the irradiation some targets were studied by Auger electron spectroscopy (AES), X-ray diffraction analysis, scanning electron microscopy (SEM), transmission electron microscopy (TEM), exo-electron emission (EEE), optical microscopy (OM), microhardness (H_μ) and surface roughness (Ra) measurements. Other irradiated specimens were annealed under vacuum ($1.33\cdot10^{-6}$ MPa) for 2 hours at 560–580 °C. Initial, irradiated and annealed samples and blades were tested for fatigue at the operating temperature (450 °C) in air with high loading frequency (3000 Hz). The fatigue tests were realized on the magneto-strictional vibrobench with the use of directly compressor blades and plane wedge-shaped specimens with double one and two-sided radius transition from the texture zone to the leading zone (Fig. 1).

Furthermore, the samples and blades were tested for erosion resistance, oxidation resistance in air at 500 °C during 500 h, corrosion resistance under the thermocycling conditions (heating up to 550 °C, coaling in sea-water under 25 °C, number of cycling of

300), and creep after thermoexposure in air at 500 °C during 100 h. The damaged or fractured surfaces of targets after tests were studied by optical and scanning electron microscopy.

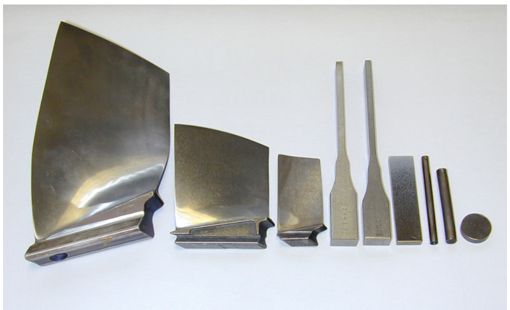


Fig. 1. Photographs of titanium alloy specimens and blades subjected to IPEB treatment

3. Results and discussion

The energy density is one of the most important technological parameter of IPEB treatment. It is well known [2] that the growth of *w* leads to the following processes into the surface layer: evaporation and sublimation of organical impurities adsorbed on the surface, high speed heating and melting of material into the surface layer with electron projected running, evaporation of surface layer elements, placed ablation (crater creation [3]), total ablation of the surface layer material and high speed solidification. These phenomena determine the physical and chemical state fixed into the surface layer and modification of part properties. Thus, it is necessary to investigate the effect of w and n on the physical and chemical state of the surface layer material and on the most important properties of targets for achievement of the optimal level of operating characteristics as a result of IPEB irradiation. The results of preliminary experiments carried out with the use of VT6, VT8 and VT9 titanium alloy samples [2,3] allow to make the classification of the irradiating regimes by the following way: w<16–18 J/cm^2 – "heat treatment regime" when high speed heating and tempering from temperature lesser than melting temperature (from β- or $\alpha+\beta$-field of the state diagram); w=18–20 J/cm^2 – "melting regime" when homogeneous melting takes place in the surface layer with thickness of 20–25 μm; w=20–45 J/cm^2 – "crater and crack creation regime" (formation of craters can lead to the creation of crack net between them); w>45–50 J/cm^2 – "total ablation regime". Some results of titanium alloy target Auger-analysis are given in [2,3]. These data allow making the following conclusions:

– The irradiation with "melting regime" leads to the redistribution of alloying elements in the surface layer (the elements with equilibrium distribution coefficients lesser 1 (K_0<1) are concentrated near the surface (Al, Fe) and the elements with K_0>1 (C, N, Mo) are ousted by the solidification front into the near-surface layer of titanium alloy targets);
– The treatment with "crater and crack creation regime" leads to the formation of pre-crystallization surface consisting single craters.

The chemical composition fixed into craters can be equivalent and/or different one of the alloy sufficiently. So high value of aluminum concentration was observed in the several craters (up to 80 at. %) and vanadium, molybdenum, carbon were the main elements in various craters. At the same time the registration of Auger-spectra on the "free" surface points the decrease of aluminum concentration that may be connected with evaporation of this element which has high value of vapour elasticity in comparison with Ti, Zr, Mo, V etc. The redistribution of alloying elements in the surface layer of titanium alloy targets subjected to the melting regime irradiation can be described by the equations of Barton, Prim, Slihter [3]:

$$C(x) = \frac{K_{eff}}{l-x}\left[\int_0^t C_0(\tau)d\tau - \int_0^t C(\tau)d\tau\right], \quad (1)$$

$$K_{eff} = \frac{K_{eff}}{K_i + (1-K_i)\exp(-v\,\delta_c/D)}, \quad (2)$$

here k_i is the equilibrium coefficient of distribution, c is thickness of the diffusion frontier layer, and D is the coefficient of diffusion.

Even according to these data it is possibly to make the conclusion on high prospect of IPEB application for surface modification of titanium alloy parts with the use of the "melting regime", because in this case the redistribution of elements leads to the increase of aluminium concentration in the surface layer. The latter allows one to improve the oxidation and corrosion resistance.

Some results of investigation of energy density effect on phase composition and structural characteristics of titanium alloy part surface layer are presented in Table 1 and Figures 2, 3. According to these results and already published data [2,3] the following conclusions can be made that the electron beam treatment leads to the formation of meta-stable α-phase and martensite α', α''-phases, residual compressive (VT6) and tensile (VT8, VT9) stresses from –300 MPa to +400 MPa, bi-modal lamellar and globular (VT6), lamellar and Vidmanstatten (VT8, VT9) microstructures [2,3].

Furthermore, a great amount of microcraters and microcracks are created on the surface of targets during irradiation with high values of *w* ("crater and crack formation regime"). It is shown that the best irradiating regime is the "melting regime" resulting in the formation of bi-modal microstructure with the average size of grains near 10–20 μm and the decrease of surface roughness from 0.30–0.60 μm to 0.15–0.32 μm. In that case craters and cracks are absent on the irradiating surface and homogeneous distribution of physical and chemical state on the surface of the irradiating blade is observed (Fig. 2, *b*). But formed residual tensile stresses (VT8 and VT9 alloys) the increase of dislocation density in the surface layer can become the reason of service property deterioration. As a result, the final vacuum annealing at 530–550 °C temperature would be carried out after the irradiation with the "melting regime".

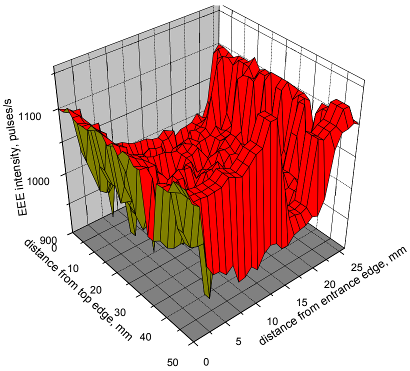
Table 1. The effect of IPEB irradiation and final heat treatment (*) on phase composition, residual stresses (σ) and half width ($h_{1/2}$) of X-ray line of titanium alloy specimens.

alloy	w, J/cm^2	n, pulse	phase composition	σ, MPa	$h_{1/2}$ ±0,008
VT8	–	–	$\alpha+\beta$ (8 %)	−220±15	1,606
VT8	18–20	1	$\alpha(\alpha')$	+310±10	1,602
VT8	26–32	1	$\alpha(\alpha', \alpha'')$	+430±40	1,610
VT8	26–28	5	$\alpha(\alpha', \alpha'')$	+460±70	1,595
VT8	32–36	5	$\alpha(\alpha', \alpha'')$	+620±60	1,599
VT8*	18–20	3	$\alpha+\beta$ (4.3)	−150±20	1,609
VT6	–	–	$\alpha+\beta$ (7,5 %)	−69±17	1,611
VT6	18–20	1	$\alpha(\alpha')$	−226±40	1,607
VT6	26–28	1	$\alpha(\alpha', \alpha'')$	+250±90	1,609
VT6	26–28	5	$\alpha(\alpha', \alpha'')$	+570±110	1,599
VT6	32–36	5	$\alpha(\alpha', \alpha'')$	+670±110	1,611
VT6*	18–20	3	$\alpha+\beta$ (6,5)	−215±20	1,604
VT9	–	–	$\alpha+\beta$ (8,6)	−369±47	1,610
VT9	18–20	1	$\alpha(\alpha')$	+266±42	1,602
VT9	26–28	1	$\alpha(\alpha', \alpha'')$	+470±90	1,609
VT9	26–28	5	$\alpha(\alpha', \alpha'')$	+490±60	1,597
VT9	32–36	5	$\alpha(\alpha', \alpha'')$	+570±4	1,599
VT9*	18–20	3	$\alpha+\beta$ (5,7)	−215±20	1,605

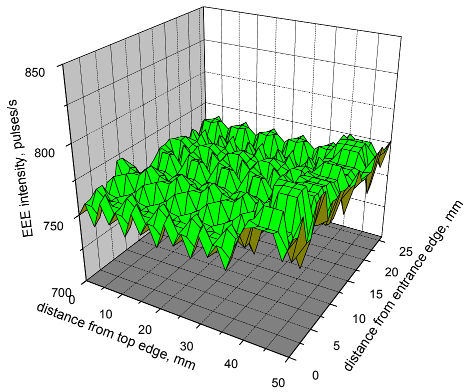
Due to the final heat treatment it is possible to stabilize the structure of the material in the surface layer, to obtain more homogeneous distribution of elements in a depth and, the main, to create residual compressive stresses of –(200–250) MPa in the surface layer. Here, it is necessary to point that residual tensile stresses cannot be removed using vacuum annealing of targets from VT8 alloy. While the final thermomechanical processing of parts from this alloy would be carried out. The transition of fine lamellar structure to bi-modal one can be realized by cyclical loading in air at 450 °C (120–180 MPa) and by heat isostatic pressuring under the optimal condition in Ar at 530–550 °C (200 MPa).

The results of VT6, VT8, VT9 titanium alloy blade fatigue tests presented in Table 2 and [2, 3] allow making the conclusion on possibility to increase the fatigue limit on the base of $2\cdot10^7$ cycles more than by 20–40 % due to IPEB irradiation, heat treatment or thermomechanical processing under the optimal conditions.

Also important result of the fatigue tests is the effect of vacuum during final heat treatment on the fatigue limit of VT9 alloy blades subjected to IPEB processing. One can see (Table 2) that stabilized annealing in vacuum below than $1.33\cdot10^{-3}$ Pa leads to the decrease of the fatigue limit. The latter can be connected with radiation-adhance diffusion of oxygen into volume layers of the targets because high defect state with the dislocation density of 10^{11}–10^{12} m^{-2} is formed in the 25-μm crystallized surface layer due to high-speed solidification. Oxygen intensively diffuses by defects in a depth of 20–25 μm during annealing [2, 3]. As a result of oxygen diffusion the microhardness increases up to 400–600 HV units when oxygen concentration in the surface layer of 20–25 μm achieves 8–20 at. %. In comparison the serial blades from titanium alloys passed vibroabrasive treatment consist oxygen in the surface layer with thickness of 400 nm [2, 3] and this fact does not lead to catastrophic decrease of the fatigue limit.



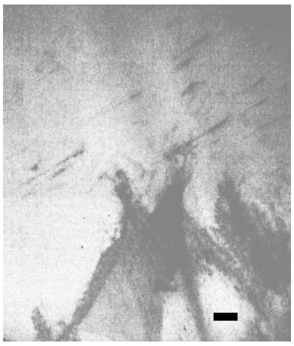
a



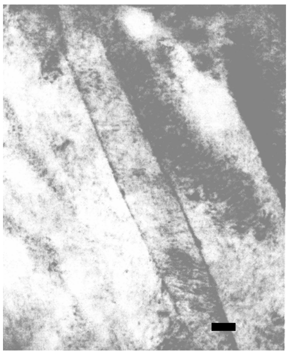
b

Fig. 2. EEE scannograms of VT9 alloy blades irradiated with electron beam: a) initial state; b) after electron beam processing with w=18–20 J/cm^2; n=2 pulses

IPEB treatment allows one to ablate the oxygen impurities from the surface layer of titanium alloy blades but the increase of point and linear defect concentration takes place in this layer due to high-speed solidification. Besides, it is necessary to carry out annealing in deep vacuum (10^{-5}–10^{-6} Pa) with the goal of oxidation rate decrease. IPEB treatment effects on the corrosion resistance, oxidation resistance and tensile creep of $\alpha+\beta$-titanium alloy samples and blades that presented in [9–11]. A rise of the oxidation and corrosion resistance after irradiation (the "melting regime") and final heat treatment or thermomechanical processing is a result of the following changes in the surface layer: the exit of aluminum on the surface; formation of resistant films on the base of aluminum and titanium oxides; ablation of surface defects; decrease of effective surface area due to reduction of surface roughness and creation of residual compressive stresses. Irradiation under the "crater creation regime" leads to decrease of the corrosion resistance. Furthermore, the most intensive corrosion processes take place into the craters. The growth of plasticity [3] fixed during the creep tests after long time thermo exposure in air can be explained by the dramatic decrease of the oxidation rate.



200 nm a



100 nm b

Fig. 3. Microstructure in the 15-μm surface layer of VT9 alloy serial (a) and irradiated (b) blades

Table 2. The results of high frequent fatigue tests of VT9 alloy blades after IPEB irradiation and heat treatment (550 °C in vacuum of $1.33\cdot10^{-3}$ Pa* and $1.33\cdot10^{-6}$ Pa**) at 25 and 450 °C in air

w, J/cm^2	n, pulse	T, °C	τ, h	σ_{-1}, MPa
–	–	25	–	490±10
18–20	1	25	–	390±20
18–20	2	25	–	400±20
18–20	3	25	–	400±15
18–20	5	25	–	400±10
32–36	5	25	–	340±30
–	–	450	–	360±20
18–20	3	450	2 (**)	390±15
18–20	3	450	4 (**)	400±10
18–20	3	450	6 (**)	420±10
18–20	3	450	8 (**)	420±10
18–20	3	25	6 (*)	350±10
18–20	3	450	6 (*)	320±10

4. Conclusion

The experimental results presented in this paper allow to make conclusion on a high effectiveness of electron beam treatment application for surface modification of $\alpha+\beta$-titanium alloy parts.

Acknowledgments

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References

[1] A. Petuhov, *Fatigue resistance of gas turbine engine parts*, Machine – Building, Moscow, 1993.

[2] A. Paikin, A. Lvov, V. Shulov, V. Engelko, Problems of Machine Building and Automation, 3, 41 (2001) (in Russian).

[3] Engelko V., Yatsenko V., Mueller G., Bluhm H., Vacuum 62, 211 (2001).