Combined Ionic Implantaion and Vacuum Placma Surface Modification of Titanium and Steel Steam Turbine Blades to Provide Service Properties

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Abstract – The cited results imply research in physiochemical condition, service property of steels 15H11MF, 20H13 and titanium alloys TS5, VT6 after combined vacuum ionic implantation and ionic placma surface modification. The given results underlay the development of technology and equipment of steam turbine rotor blade hardening, which provides considerable increase in service properties, reliability and durability.

Being the most loaded and critical part of steam turbines, rotor blades (RB) of the last stages of low-pressure cylinder (LPC) operate in difficult conditions of droplet erosion, corrosive effect and alternate stress. This service effect results in wear and damage of edges, fatigue failure and breakage of a fan and different sized surface corrosion pits. Longstanding statistical result research in cogeneration turbines T-100-130 and T-250/300-240 operating showed that because of RB damage their operation life made up in average 50 000 hours [1].

To increase droplet erosion resistance leading edges when being produced are protected by brazing and welding of stellite shields [2] (at JSC "Leningrad Metal Factory" (LMF), Saint-Petersburg city and JSC "Ural Turbine Motor Factory" (UTF), Ekaterinburg city), by electric-spark coating deposition and by HFC-quenching hardening (at "Turboatom", Kharkov city) etc. [3].

However, the given ways of RB protection do not solve the problem to a full extent and they are of the following drawbacks: erosion resistance is increased on separate parts of blades; different edge effects stimulating corrosion processes emerge at the boundary of hardened and non-hardened parts; overhanging stellite shields do not only decrease fatigue strength but degrade aerodynamic properties of a blade; practically all applied technologies change physiochemical condition of a surface and result in additional concentrator of tension. The results of our teamwork with JSC "UTMF" and JSC "Mosenergo" are submitted in Table 1.

Steels 20H13, 15H11MF, EI-961 are widely used to produce RB but last decade last century titanium alloys VT6, TS5 started to be used because of their high mechanical and corrosion properties.

As for blades of titanium alloys the given ways of protection and methods of coating deposition in air space did not turn out to be acceptable because of the mentioned above drawbacks and also because of high surface gasing, concentrators of tension and cracking.

In this connection we can draw a conclusion that nowadays technologies providing droplet erosion resistance, fatigue strength and corrosion resistance of RB made of steels and titanium alloys are not so far worked out.

The most perspective way to change service properties of RB is vacuum ionic implantation and ionic plasma technologies [4] having been already applied to harden gas turbine blades [5, 6]. As for steam turbine RB suffering from high droplet effect special technologies are necessary to be worked out to harden a substrate and to protect it by way of additional coating.

The most perspective methods to solve the hardening problems of large-sized RB ($L \geq 1500$ mm and $m \sim 20$ kg) made of steels and titanium alloys in steam turbines are plasma ones. They are used in a single vacuum room and comprise electronic, ionic implantation surface modification with subsequent ionic plasma coating deposition on the basis of nitrides and carbides of refractory metals.

Table 1. The fatigue test results of specimens of steel 20H13 treated by different technological variants

Specimen state	Fatigue limit σ_{-1}, MPa based on 10^7 cycles (air)	Fatigue limit σ_{-1}, MPa based on 10^5 cycles (corrosion environment)
Initial	320	180
Stellite brazing	90	80
Stellite welding	60	50

Taking into account the problem urgency we have worked out the technologies of combined hardening and the equipment to apply them on for LPC RB of steels and titanium alloys in steam turbines. The technologies being worked out the following was conducted: research in feasibility of ionic gas source and devices for metal plasma production to treat large-sized blades of steam turbines in vacuum; examination of physiochemical condition of the surface coating and mechanical properties in connection with combined vacuum ionic implantation and ionic plasma treatment; working out of combined treatment mode; test of service properties after combined treatment; elaboration of technologies and equipment to hard steam turbine RB using combined treatment.

At present there are different gas sources to conduct ionic implantation: high-energy pulsed (En = 20–500 keV, j = 50–150 mcA/cm^2); high-energy with continuous action (En = 20–80 keV, j = 10–50 mcA/cm^2); low energy sources of low pressure gas volume discharge ($En \leq 1$ keV); low energy sources of breakdown placma of low pressure semi-self-maintained arc discharge with hollow cathode ($En \leq 1$ keV, j = 15 mA/cm^2); low energy sources on the basis of double-stage vacuum arc discharge (En = 1 keV, j = 15 mA/cm^2).

At elaborating of the technologies low-energy implantation was assumed as the basis, which had the following advantages: high penetration depth of doping elements, low temperature surface heating, residual stress removal after mechanical operation, high service properties (σ_{-1}, wear resistance) combined with treatment manufacturability and economy.

The requirements of gas plasma sources for ionic implantation treatment are the following: ionic current density j = 5...10 mA/cm^2; irregularity of ionic current density at section ≤ 10...15%; beam diameter no less than 300 mm; possibility of transformation from axial-symmetric plasma sources into distant ones for uniform illumination of large-sized articles; wide range of plasma generating gases (argon, nitrogen, acetylene, etc.); design simplicity, low cost; compatibility with other plasma sources at simultaneous work in a single vacuum room; service stability and durability.

The requirements for metal plasma sources providing refractory coating deposition are the following: high speed of coating deposition ($v \geq 20$ mcm/h); beam diameter no less than 200 mm with irregularity no more than 5% at coating thickness; high ionicity of evaporable material; a minimum of drop phase; evaporation possibility of refractory metals and their alloys; possibility of transformation from axial-symmetric plasma sources into distant ones; design simplicity, low cost; compatibility with other plasma sources.

“Stankin” gas sources of neutral molecule (MSTU, Moscow city) draw attention and meet the mentioned above requirements. MAI source (Moscow city) treats large areas with high uniformity at section and is able to operate at mode of “before ion acceleration” by negative removal application to a treated article.

There are technological gas sources with incandescing cathode (Tomsk city), which produce the highest ionic current density; such discharge plasma is able to generate simultaneously with metal plasma and assist to deposit coatings.

Double-stage vacuum arc discharge is of interest to decide the question of ionic implantation and ionic plasma treatment with one device application.

Double-stage vacuum arc discharge application allows to use one and the same plasma source for ionic implantation and also for subsequent coating deposition. In connection with this the design of a vacuum plant is significantly simplified. The technologies being elaborated MAI gas source was assumed as the basis, which was built into vacuum volume at ELU-9B plant. A gas source with incandescing cathode (Tomsk city) was applied to harden steel specimen at treatment. To treat steel blades double-stage vacuum arc discharge was recommended, which allows to simplify significantly a vacuum plant for industrial application and also to get properties similar to the source (Tomsk city).

Coating deposition was carried out by way of electroarc evaporator application that meets the requirements put by.

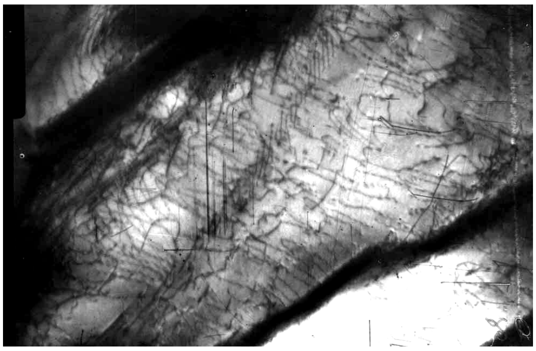
To test the combined technologies a pilot plant was designed that operates the mentioned above processes.

The examination of physiochemical changes in steels and titanium alloys VT6, TS5 in connection with combined vacuum ionic implantation and ionic plasma treatment was conducted by way of optical and electronic microscopy, Auger spectrometer and X-ray crystal analysis.

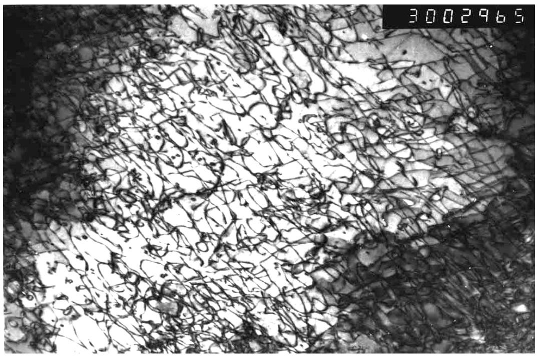
The process of low-energy ionic implantation goes with nitrogen ions penetration up to 8…10 mcm depth, which results in formation of solid solution of penetration and hardening nitride phase, significant change of dislocation arrangement: increase in dislocation density and structure formation close to a grid one up to 80…100 mcm (Fig. 1).

The distribution of microhardness in a modified ionic implantation layer is given in Fig. 2. The similar character of microhardness change was noticed on steels 20H13 and 15H11MF.

The revealed changes of structural and phase composition of material surface layers provide dislocation, solid solution and dispersed hardening (see Fig. 1). Meanwhile the sprayed and activated surface intensifies its interaction with TiN deposited coating that significantly increases adhesion strength of the coating with the substrate. Besides, nitrite phases formation provides graded junction of physiochemical properties with TiN coating. The substrate plasma heating before coating deposition provides its postimplantation annealing.



a



b

Fig. 1. Structure of specimen surface made of steel TS5: *a* – initial state (mechanical polishing), $\rho = 3.5 \cdot 10^8$ cm^{-2}; *b* – implantation state, $\rho = 17.3 \cdot 10^9$ cm^{-2}

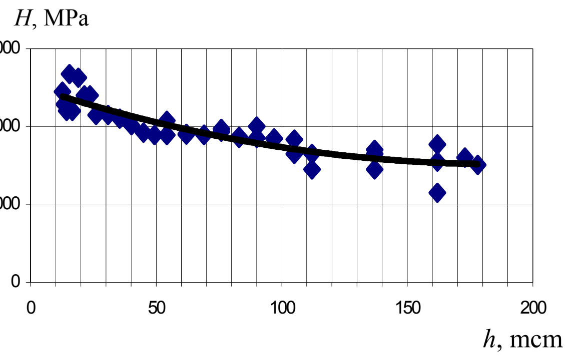


Fig. 2. Microhardness of alloy TS5 layer modified by ionic implantation at 50 g loading

Titanium alloys were deposited with one-layer TiN coating 8 mcm thick with Ti sublayer 0.5–0.8 mcm thick. Steels were deposited with a multi-layer of 4 x (Ti – TiN) system 20–25 mcm thick. Multi-layer structure application allowed to increase corrosion resistance of steels 20H13 and 15H11MF up to 20 times.

Deposited ionic plasma coatings have surface microhardness $H_v \geq 15000$ MPa (Fig. 2) and heterogeneity no more than 8%. Such coatings provide hardness increase in more than 3.5 times in comparison with a non-modifying surface.

The microstructure of alloy BT6 specimen with a coating is given in Fig. 3, that of alloy 20H13 is in Fig. 4.

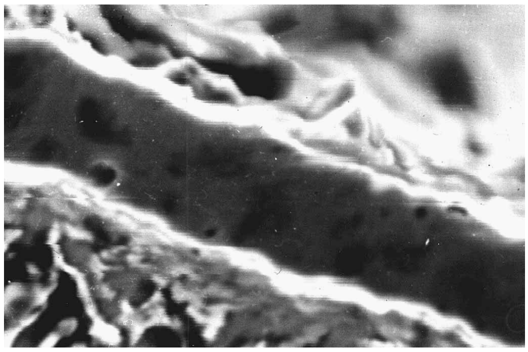


Fig. 3. Coating microstructure deposited on alloy VT6 (1000x)

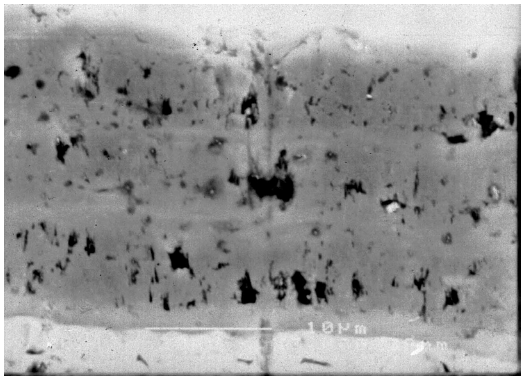


Fig. 4. Coating microstructure deposited on alloy 20H13 (1000x)

The research of the formed physiochemical condition of titanium alloy TS5 and VT6 surface coating underlay the mode elaboration of ionic implantation and ionic plasma treatment namely in a ultrasonic bath, in a vacuum chamber up to $p = 10^{-3}$ Pa pressure; surface ionic implantation modification by nitrogen $D = 2 \cdot 10^{18}$–$2 \cdot 10^{19}$ ion/cm^2 at ionic current density $j = 1\ldots10$ mA/cm^2 and accelerating voltage $U = 0.3\ldots1$ keV; postimplantation annealing and heating by Ti ions before coating deposition up to 400…500 °C temperature; one-layer and multi-layer TiN or Ti–TiN coating deposition at speed 20 mcm/h with uniformity of coating thickness no less than 8% at assisting of gas plasma deposition.

According to the mentioned above modes we treated the specimens of alloys TS5, VT6 and steels 20H13, 15H11MF and defined their service properties. The results are given in table 2 and in Figs. 5, 6, 7.

The steam wet erosion resistance was determined according to the method and at the bed of the Moscow Power Institute.

The determination of fatigue resistance was conducted according to GOST 9.302-88 requirements at temperature 20 °C at the bed with U-335 vibration generator.

The adhesive adhesion strength was defined by glue method.

The research in service properties of steels and titanium alloys shows: significant increase of fatigue resistance in air space and in corrosion environment (Figs. 5, 6, 7); increase of droplet erosion resistance in 1.5–3.0 times (Table 2); increase of adhesive resistance in 1.6 times; increase of corrosion resistance.

Table 2. Testing results of service properties of steels VT6 and 20H13 specimens

Treatment variant	Relative erosion resistance		Adhesive strength, MPa
	latence period, $E_{relat.}$	accelerated erosion, $E_m \cdot 10^{-3}$	
VT6 initial state	1.3	1.5	
20H13 initial state	1	1.95	
Nitrogen implantation + TiN (9 mcm) BT6	2.6	0.65	>> 150
Nitrogen implantation + TiN (20 mcm) 20H13	2.85	0.5	>> 150

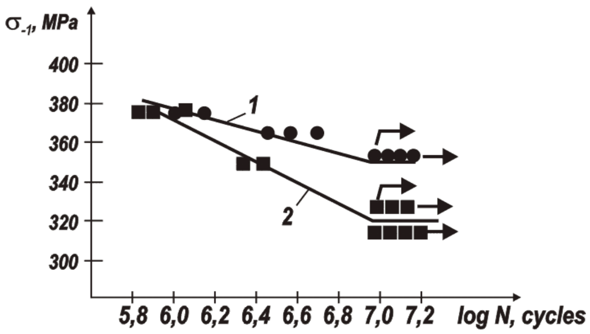


Fig. 5. Curves of fatigue of steel 20H13 specimens in air space: *1* – ionic implantation + multi-layer Ti-TiN coating; *2* – raw specimens

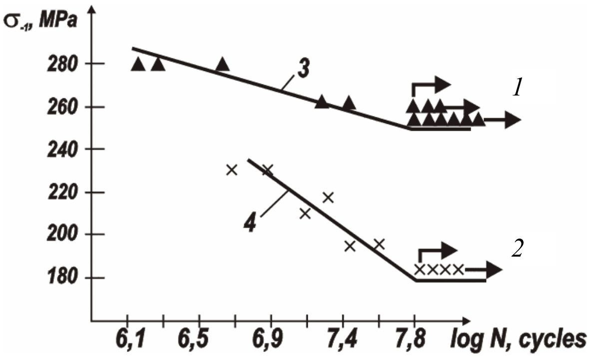


Fig. 6. Curves of fatigue of steel 20H13 specimens in corrosion environment *1* – ionic implantation + multi-layer Ti-TiN coating; *2* – raw specimens

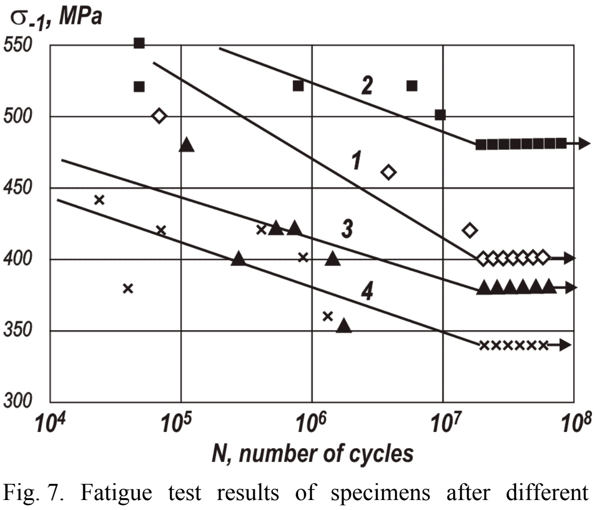


Fig. 7. Fatigue test results of specimens after different treatment variants *1* – initial state*;* *2* – ionic implantation + + TiN coating (h = 8–9 mcm); *3* – supersonic coating deposition; *4* – detonation coating

The positive research results underlay the technology development of turbine RB made of steel and titanium alloys VT6, TS5.

To apply the hardening technology to steam turbine blades we have designed “Maria” vacuum plant to treat titanium blades.

The plant allows to realize the following for large-sized articles made of structural materials: electronic heating by way of semi-self-maintained low pressure arc discharge with current I_p = 150–800 A; ionic implantation surface modification applying radiation-enhanced diffusion of doping ions that provides dislocation, solid solution and disperse hardening and also ionic doping by way of plasma acceleration with ion current density j = 1–10 mA/cm^2 and accelerating voltage U = 0.3–1 keV; surface cleaning by Ar^+, Ti^+, Cr^+, Ta^+, V^+ etc. ions with subsequent coatings deposition of these metals and also coatings of carbides and nitrides of metals at speed up to 20 mcm/h and depth uniformity no more than 8% at length up to 1500 mm; assisting of coating deposition of metals, carbides and nitrides by ions of gas plasma that is generated by plasma acceleration.

The outward appearance of “Maria” plant is given in Fig. 8 and that of blades is in Fig. 9.

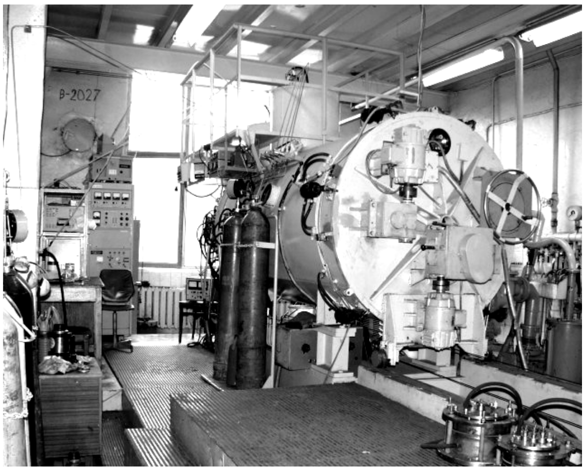


Fig. 8. Outer view on “Maria” plant

The developed technologies and equipment are applied at FSUE “SPE “Motor” (Ufa city). Steam turbine RB of titanium alloys treated according to the given technology are operated at power stations in Finland, Iran, China and installed at the power station in India.

Fig. 9. Blade surface appearance after treatment

For steel blades we have designed and produced "Victoria" vacuum plant with a vertical way of blade fastening that at present is being tested at SUE "UFM "Magnetron" (Ufa city). Steel blades are operated in a test turbine at JSC "Mosenergo".

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