Fretting Resistance of Steam Turbine Blades of Titanium Alloys by Ion Implantaion and Vacuum Plasma Surface Modification

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Abstract – The examination of BT6 specimens showed that nitrogen ionic implantation with subsequent deposition of vacuum plasma coating of titanium nitride (Ar+i.i.+Ti) is the most perspective hardening method of titanium alloys and can be applied to increase their fretting resistance.

1. Introduction

At present the problem of fretting resistance for high-powered steam turbines is vital and not so far solved. Its most urgent part concerns contact surface protection of rotor blades (shanks, strip and antivibration shelves, Fig. 1) where fretting development can cause the whole turbine breakdown and outage.

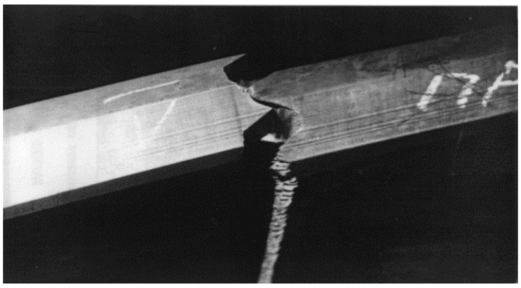

Fig. 1. Fretting wear of steam turbine blades

Fretting emerges in the joint position of mating components, which under load microtraverse at amplitude of several tens micrometers, for example, at vibration. As a result of such small amplitude detail surface fracture occurs at a contact patch and is of fatigue and corrosion character. In addition we remark metal generation, caving, pitting, surface microcrack nucleation and their development and as a consequence abrupt decrease of article durability [1–4].

Nowadays in a great number of works dedicated to the research in reliability increase of details operating at fretting [1, 3, 4, 8] we observe lack of universal ways of this process protection. Meanwhile there are general approaches considering decrease or prevention from factors causing fretting. A. Bartel in 1964 attempted to systemize different means to prevent fretting and singled out 4 main groups: constructive, mechanical, material selection, installation and industrial ones [1]. They are evident to be added by a wide range of technological treatment methods starting from mechanical effect choice to provide required surface quality up to protective coating deposition with hardening ionic implantation and vacuum plasma methods of surface modification.

One of the most perspective methods of surface treatment which a number of researchers [5, 6] connects with significant increase of service properties of machine details is vacuum plasma and ion implantation technologies. The advantages of these treatment variants are at present used to a full extent to produce critical parts of gas turbine engines [7] operating at high temperatures, pressure and corrosive medium. Besides, they used to be applied to increase effectively wear resistance of metal cutting tools made of high-carbon, high-speed steels, hard alloys and also upsetting tools (dies, rams), extrusion and drawing tools, tribological situation and stamping tool sets; to raise corrosion resistance and cyclic durability of different machine parts [6].

Different combined methods of ion-beam surface modification are worked out on the basis of ionic implantation that are effectively used to treat details operating in difficult service conditions, for example, at simultaneous combination of alternating voltage, corrosion environment, erosion wear and temperature. These methods imply combined ionic bombardment of a surface, heat treatment and subsequent vacuum plasma protective coating deposition. The treatment process is conducted in three stages. At first, to clean and activate the surface the ionic effect is carried out with small energies of 10^2–10^3 eV. Then, when ion energy is increased up to 40 keV we observe the process of ionic implantation and compression creation in a coating surface at its simultaneous solid solution hardening. After, on the final stage of treatment ion energy is decreased and protective coating is deposited to provide wear resistance and anticorrosion surface properties. Thus, the modified surface created as a result of such combined treatment is characterized by different densities of radiation defects, new chemical combinations and is of unique physiochemical and service properties that are not so far examined.

The advantages of vacuum ionic implantation treatment are the following. It is possible to get practically any combination of matrix doping elements and to carry out the process of ionic doping at any temperatures including normal and negative ones. Dopants can be introduced in strict dozes, i.e. it is possible to dope contact surfaces with expensive materials. We observe practical invariability of geometric shape of a treated detail, lack of warping. The process is absolutely ecologically clean, simple to operate with its characteristics, possible to get assigned profiles of dopant bedding and also to treat local surface areas [6, 8]. In this connection there is a rather interesting problem of examining fretting resistance increase of details by methods of ionic implantation and vacuum plasma surface modification that form its unique structure impossible to get by any other methods of treatment.

2. Experiment and Investigations

The experiment to examine fretting resistance was carried out according to the following method. The cylindrical moving test arbor made of examining material is in contact with orifice surface of a non-moving countertest hub at the cylindrical outer surface (Fig. 2). After external force being applied the counterspecimen is assigned with vibration of a given amplitude and frequency. The arbor wear was measured at the end of basic quantity of detail interaction cycles. The plant for "arbor-hub" fretting testing is given in Fig. 3.

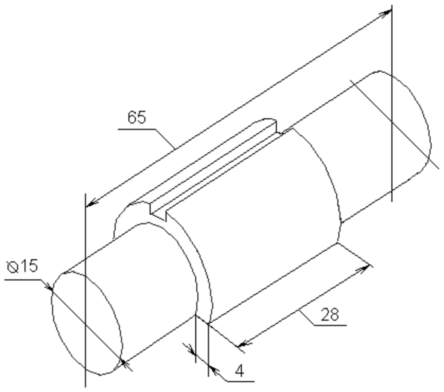

Fig. 2. Testing conjugate "arbor-hub"

Testing on fretting resistance was conducted on titanium specimens (alloy BT6) treated according to the following variants:

variant 1 (initial state): polishing 0.32 Ra;

variant 2: initial state + argon treatment + nitrogen ionic implantation (Ar + i.i.);

variant 3: initial state + argon treatment + titanium nitride magnetron coating (Ar + TiN);

variant 4: initial state + argon treatment + nitrogen ionic implantation + vacuum plasma titanium nitride coating (Ar + i.i. + TiN).

In cooperation with JSC "Leningrad Metal Factory" (Saint Petersburg city) the following fretting testing modes were assumed according to the long-standing experience of steam turbine production and operating and the analysis of rotor blade failure:

– specific pressure at contact surface $p = 1$ kgs/mm^2 (10 MPa);

– frequency of relative vibration f in the range of 100–130 Hz;

– creeping quantity $2Am$ = 100–125 mkm.

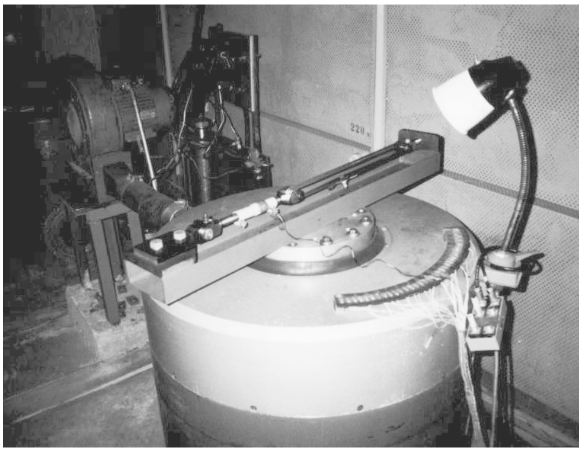

Fig. 3. Outward appearance of plant for specimen fretting testing (on the basis of ВЭДС-1500 vibrobed)

To assess and comparatively analyze the hardening research method after fretting test the following was conducted:

– metallographic examination of specimen surface;

– unsoundness examination of specimen surface according to its roughness change;

– weakening examination of specimen surface according to microhardness criterion.

Metallographic examination of specimen surface after fretting test

The surface in the area of contact patch was examined on NEOPHOT-21M light microscope at magnification of 600x.

While testing the specimens made of titanium alloy BT6 on fretting resistance after polishing (in the initial state) we observed defected surface in the form of tear-outs, light rubbings and dark oxide spots that indicated its intensive failure.

The worn specimen surface treated according to variant 2 (nitrogen i.i.) implies combination of hairlines without visual surface oxidation. Material seizure at friction was not observed.

Table 1. Test results on roughness

Variant of technological method of treatment	Before fretting			After fretting		
	Ra1	Rmax1	Rz1	Ra2	Rmax2	Rz2
1. initial state	0.32	2.51	2.2	2.5	43.6	29.48
2. Ar+i.i.	0.32	3.68	2.38	0.33	5.28	3.22
3. Ar+TiN	0.22	3.13	2.07	0.69	10.2	6.87
4. Ar+i.i.+TiN	0.23	2.48	1.84	0.49	5.09	3.81

Table 2. Change of roughness characteristics as a result of fretting

Variant of technological method of treatment	Before fretting		
	Ra2/Ra1	Rmax2/Rmax1	Rz2/Rz1
1. initial state	7.81	17.38	13.40
2. Ar + i.i.	1.03	1.43	1.35
3. Ar + TiN (magnetron coating)	3.14	3.26	3.32
4. Ar + и.и. + TiN (vacuum plasma coating)	2.13	2.05	2.07

Table 3. Test results on rate of surface deformation *k*

Treatment variant	Before fretting, *k*1	After fretting, *k*2	Change as a result of fretting *Dk* = *k*2/*k*1
1. initial state	0.873	0.943	1.08
2. Ar + i.i.	0.913	0.938	1.03
3. Ar + TiN (magnetron coating)	0.930	0.932	1.00
4. Ar + и.и. + TiN (vacuum plasma coating)	0.907	0.904	0.99

The specimens treated according to variant 3 (Ar + TiN) are of smooth surface coloured bronze without its visual defects (droplet phase, surface discontinuity flaw and etc.). As a result of fretting on the specimen surface there was a contact patch with dark oxide spots and dark rubbings with seizure marks in the line of friction.

The specimens treated according to variant 4 (Ar + i.i. + TiN) are of bright yellow surface without its visual defects (droplet phase, surface discontinuity flaw and etc.). As a result of fretting on the specimen surface there were local light rubbings in the line of friction without seizure marks.

Examination of specimen surface unsoundness in its roughness change

The roughness examination was conducted by way of Talyrond trace removal from the specimen surface before and after fretting according to standard methods on HEMMELWERK T-500 profilograph-profilometer with automatic calculation and PC data recording.

Roughness parameters measuring:

– basic length *Lt* = 15 mm;

– cutoff length *Lc* = 0.8 mm;

The test results are given in Tabl. 1–3.

To analyze the influence of each treatment variant we have calculated the parameter of surface unsoundness rate $k = 1 - Ra/Rmax$, so as at surface tension concentrate ($Rmax >> Ra$) $k \to 1$. Besides, the parameter $dk = k2/k1$ (Tab. 3, Fig. 4) allows to testify the dynamics of roughness parameters change *Ra* and *Rmax* as a result of fretting in the following way.

The decrease of unsoundness rate $dk < 1$ ($dk2 < dk1$) shows that as a result of fretting *Ra* unsoundness quantity increases faster than the quantity of maximal profile displacement *Rmax* that testifies the normal uniform wear process without surface tension concentrates (different defect: tear-outs, microcracks, etc.).

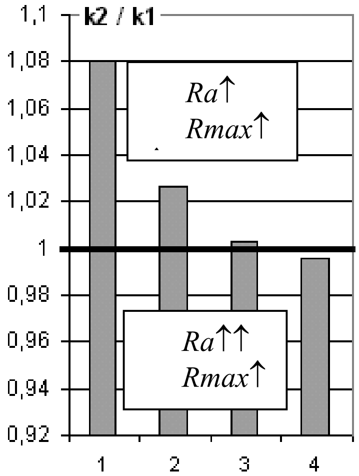

Fig. 4. Unsoundness change as a result of fretting

At increase of $dk > 1$ ($dk2 > dk1$), on the contrary, *Rmax* quantity increases faster than *Ra* quantity that testifies high profile displacement, emergence of different defects and tension concentrates.

Table 4. Examination results in microhardness Hv(20), MPa

Variant of technological method of treatment	Before fretting	After fretting	Decrease as a result of fretting, times
1. initial state	3648	2695	1.4
2. Ar + i.i.	6188	6228	0.99
3. Ar + TiN (magnetron coating)	6381	4873	1.3
4. Ar + i.i. + TiN (vacuum plasma coating)	14386	12207	1.2

Table 5. Examination results in microhardness Hv(50), MPa

Variant of technological method of treatment	Before fretting	After fretting	Decrease as a result of fretting, times
1. initial state	4372	3642	1.2
2. Ar + i.i.	6188	6228	0.99
3. Ar + TiN (magnetron coating)	3196	2194	1.4
4. Ar + i.i. + TiN (vacuum plasma coating)	10968	9734	1.1

Taking into account the above mentioned we can draw a conclusion that variant 4 (Ar+i.i.+TiN vacuum plasma coating) is more preferable than other examined methods of treatment preventing from surface defects development at fretting corrosion.

Weakening examination of specimen surface by microhardness criterion

The fretting corrosion resistance of examining specimens can be evaluated by the surface microhardness criterion. The more microhardness quantity decreases the more intensive weakening is. It goes with emergence of surface defects and secondary products of wear in the contact zone (oxide film, metal microparticles) that significantly increases the possibility of conjugate failure, fatigue damage development, breakdown.

It is evident that by microhardness criterion the most favourable treatment will be the one to provide minimal surface weakening as a result of fretting corrosion test.

The microhardness examination of specimen surface made of titanium alloy BT6 after different methods of hardening treatment was conducted on NEOPHOT-21 device at loads of 20 g and 50 g according to the standard method.

The measure results are given in Tab. 4, 5, Fig. 5. The findings allow to testify initial resistance change of small surface layers (of 2–5 mkm) as a result of fretting.

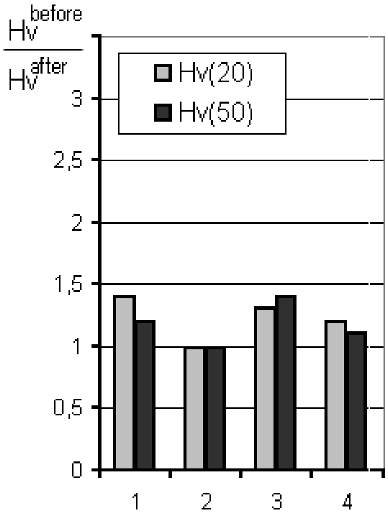

Fig. 5. Microhardness change as a result of fretting corrosion test

On the basis of finding analysis of specimen surface weakening examination by microhardness criterion we can draw a conclusion that:

variant 2: Ar + i.i.;

variant 4: vacuum plasma coating Ar + i.i. + TiN are more preferable (microhardness decrease no more than 30%, Fig. 5) than other examined methods of treatment.

Taking into account the findings and unsoundness examination results of specimen surface in its roughness change we can confirm that the highest fretting corrosion resistance of specimens of titanium alloy BT6 is provided by variant 4 (Ar + i.i. + TiN) technological method of treatment.

Besides, additional examination in fatigue limit σ_{-1} showed that the specimens treated according to the selected method provided its level $\sigma_{-1} = 480$ MPa that is 20% more in comparison with the initial state $\sigma_{-1} = 400$ MPa.

3. Results Discussion

Each material is known [1, 6] to have a definite structural phase condition corresponding to minimal wear. It was earlier determined that at nitrogen ionic implantation with subsequent annealing (at coating deposition) in a thin surface layer we observe the mesh emergence of fine-dyspersated nitrides that decelerate dislocation exit to a surface and thus harden it. We can suppose the examined surface modification by nitrogen ionic implantation with subsequent vacuum plasma coating deposition of titanium nitride TiN provides creation of such detail surface structure that can stand multiple alternating strain without defects and damages accumulation.

One of the peculiarities of conjugate surface fretting is creation of alternating symmetrical tangential voltages. As a result of their functioning dislocations slide along the modified surface layer but do not accumulate close to it. Such dislocational movement and also increase of diffusion intensity of implanted into surface nitrogen atoms with creation of Kotrell atmosphere round structural defects facilitates material structure hardening without loss of its plasticity.

Thus, we can conclude that at hard mechanical operating self-organization processes define ionic modification surface structure in many respects. It provides significant wear resistance increase due to adjustment of surface structure to the active scheme of deformation mode providing its minimal wear.

4. Conclusion

The alloy BT6 specimen examination showed that nitrogen ionic implantation with subsequent vacuum plasma coating deposition of titanium nitride (Ar + i.i. + Ti) was the most perspective method of detail hardening made of titanium alloys and could be applied to increase their fretting resistance. On this basis a technological process was worked out that included polishing, treatment by argon, nitrogen ionic implantation with subsequent vacuum plasma coating deposition of titanium nitride of h = 8–9 mkm thick. It was recommended to harden titanium CLP rotor blades of last stages in PS "Alholma" turbine (Finland), at JSC "Leningrad Metal Factory" (Saint Petersburg city).

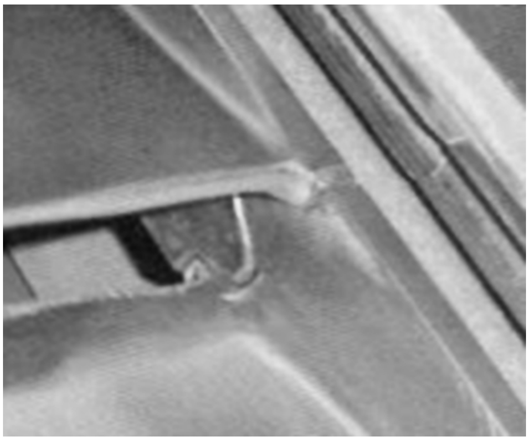

Fig. 6. Shroud view of CLP blades of PS "Alholma" turbine after 13 388 operating hours

The inspection results showed that wear marks, radial batters, cracks and other damages marks were not detected on the contact surfaces of shroud shelf cogs and shank chips, Figs. 6, 7. The condition of the contact surfaces of shroud shelf cogs and shank chips was concluded to meet the requirements of the factory and is in a perfect condition.

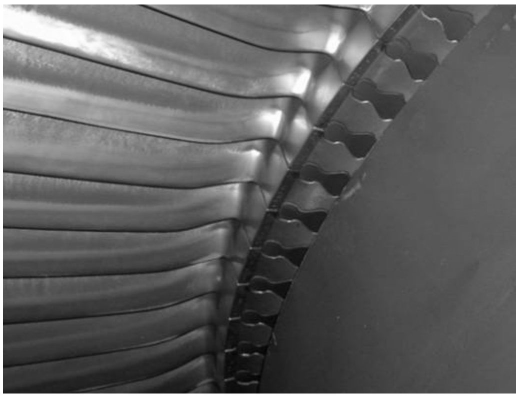

Fig. 7. Shank view of CLP blades of PS "Alholma" turbine after 13 388 operating hours

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