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State-Of-The Art, Problems and Methods to Improve Erosion Resistance of Materials Used for Manufacturing of Turbines.

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ABSTRACT

The authors depict the state-of-the art and the problems associated with droplet impact erosion of functional surfaces of components of power equipment and discuss the advantages of ion-plasma technologies which have good prospects for improvement turbine blade materials erosion resistance. They offer a conceptual solution to improve erosion resistance of components of power equipment due to the ionic or plasma depositions on their surfaces forming multifunctional protective coatings in combination with modification of the protected surfaces. According to this concept, first of all, the protected surfaces must be modified down to a depth of several tens to several hundreds of micrometers, for example, through plasma-chemical modification or modification of the subsurface layer with the use of high energy ions leading to compression of the subsurface layer and therefore increase of its hardness gradient thus repairing defects occurring in the subsurface layer. Then on the modified surface formed wear-resistant layers of ionic – plasma coatings, i.e. very hard layers of nitrides and carbides of metals (Me_xN_y, Me_xC_y), alternating with layers of pure metal (Me) that reduce internal stress. Suitable materials for erosion resistant coatings include nitrides, carbides, carbon nitrides Ti, TiAl, Cr and in particular protective multilayer coatings based on titanium aluminum nitride (TiAlN) and chromium nitride (CrN) alloys.

Keywords: rotating blades of steam turbines, droplet impact erosion, vacuum ion-plasma technologies, erosion resistance, protective coatings, modification of the surface

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STATE–OF-THE–ART AND PROBLEMS ASSOCIATED WITH EROSIVE WEAR

The progress in turbine technology and improvement of turbine efficiency depend to a large extent on the operating characteristics of turbines. The major challenges facing the power industry include maintaining uninterrupted and reliable operation and extension of service life of turbine components.

Both in Russia and abroad there is a tendency towards an increase in steam pressure (up to 35 MPa) and steam temperature (up to 700÷750 ºC) in order to improve energy efficiency and reduce costs related with power production due to using or designing modern power-generating units operating at supercritical temperatures and pressures.[1-4].

In recent times turbine manufacturers all over the world sought to increase the power of steam turbines on account of increasing the pressure and/or temperature of the steam and also on account of increasing the length of the last-stage blades of powerful steam turbines [5-8], which use would enable reducing both the losses due to residual steam velocity and the number of low-pressure cylinders and at the same time increase the power output, while the pressure in the condenser is lower.

As the size of the last-stage blades determines the number of low-pressure cylinders and the overall size of the turbine and therefore the overall size of the power-generating facility, the design and manufacturing of super long blade influences to a large extent the *electricity generation costs* including power plant design costs. Super long blades must be designed to have high strength characteristics and endure high operating loads also in two-phase working environment influence.

The analysis of the data on the damage of channels of steam turbines [9-10] provides evidence of the fact that the most commonly damaged turbine components are the last-stage blades of steam turbines that are subject to impingement by high-speed droplets causing their wear and also the blades in the phase transition zone containing primary condensate, i.e. a corrosive medium causing corrosion of the blades' surfaces.

The erosive or corrosive damage of rotating blades is the main culprit responsible for turbine downtimes and high repair costs and therefore determines the cost-effectiveness of turbines [11-16].

The breakage of rotating blades is quite often caused by erosion or corrosion or both of them. The data on erosive wear of last-stage blades of various steam turbines averaged over 6-8 years of operation provide evidence that the depth of erosive wear can reach several tens of millimeters, and in the peripheral parts of blades it can reach 30% of the chord of the profile of the blade [17]. Besides, droplet impact erosion is the culprit with lower cost-efficiency of turbine stages with eroded blades due to profile losses caused by the increased surface roughness, over-the-tip leakage (leakage through the gap between the blade and the casing wall), etc. The worst impact on the cost efficiency of turbines is produced by erosive wear of the last-stage blades as the latter generate more power than the other turbine stages.

The existing data of rotating blades metal loss due to erosion suggest that the performance of powerful steam turbines decreases by 1% behind 3 years of operation and by 5% behind 6 years of operation [18]. The losses virtually double each year and behind 4-5 years of operation the blades must be replaced. [19]. The average losses caused by erosion over the period before the turbine overhaul and/or replacement of the last-stage blades (approximately 6 years) amount to almost 9%. For example, the annual losses due to erosion of the entering edges of the water-steam last stage-blades of powerful turbines can reach 5 million rubles [20]. Besides, if one takes into account the ever increasing environmental damage due to over burning of fuel as a result of a lowered performance, today the necessity to increase the resistance to erosion is out of question.

The length of the last-stage steel blades of currently operating turbines reaches 1200 mm. If the steam pressure and/or temperature are increased, the blades would be 1400-1500 mm long, the turbine rotor speed would be equal to 50 Hz; thus the circular speed of the blades of the peripheral water-steam stages will increase up to 800 meters per second. At such speeds the droplet impingement intensifies the erosion of the entering edges of rotating blades, so that the problems related with erosive wear would be deepened. Therefore a major challenge is to develop new high-strength materials, new compositions of multifunctional protective coatings and various methods of modification of functional surfaces of rotating blades that would jointly improve the resistance to impingement by high speed droplets. Today the solution is sought by materials scientists and surface engineers.

At present there exist neither approaches nor hints to technologists how to select a coating and how to modify its surface in terms of composition, structure, thickness or depth in order to increase resistance to erosion caused by impingement of the last-stage blades of steam turbines by high-speed (up to 800 m per second) droplets.

The authors of this work offer practical solutions for increasing the erosion resistance of materials used in turbine power engineering through extension of the applications of the existing coatings in combination with modification of the protected surface.

PROSPECTS FOR THE USE OF VACUUM TECHNOLOGIES FOR THE FORMATION OF COATINGS

Global practice of the power equipment elements protection various methods use provides evidence that modern ion-plasma technologies of functional surfaces modification and protective coatings formation in vacuum together with employment of new constructional materials [21-25] can significantly extend the service life of the equipment, increase energy efficiency and reduce costs and work efforts due to the reduction of downtime due to unscheduled repair.

Coatings can effectively improve resistance to various kinds of wear being tailored to operating conditions. Coatings that are only several micrometers thick are suitable for modification of surfaces and optimization of the properties of thick materials at a nano-level, because one can have control over their growth and consequently their functional properties at the stage of their synthesis.

Research shows that the coating's thickness of 6-15 micrometers is sufficient for protection from wear due to unique properties and special structure of such coatings, because in case of a thin film wear geometry is on a submicron scale. Today the vacuum technologies are the most efficient methods of synthesis of such coatings.

Vacuum deposition allows to replace expensive materials by cheaper ones, at the same time ensuring high quality of coatings. Such processes are environment-friendly. They do not generate by products to be utilized. Therefore there exist no problems associated with dustiness and/or pollution.

Vacuum technologies enable formation of coatings of virtually any materials or alloys including heat-resistant films (nitrides, carbides and oxides) on surfaces of metals and polymeric and composite materials.

The major advantage of vacuum technologies is the generation of highly ionized plasma of sprayed metal so that at temperatures in the range from 400º to 1500ºC it is possible to ensure high adhesion of the coating to the substrate, formation of metal-nonmetal compounds and absence of porosity in the coating. In this temperature range no other technologies can achieve such results.

If compared with other technologies, for example, with the use of chemically active substances (acids, alkalis, etc.), vacuum technologies have important technological advantages:

1. Regulation of the rate of processes and smooth control of the process parameters via changing the parameters of the electric current and the accelerating voltage;
2. Simplicity of implementation. A single 'coating deposition cycle' can comprise cleaning of the surface, formation of the coating and modification (optimization) of the surface
3. High purity. Vacuum treatment of an item/ products with contaminants-free coating

Usually the concept "vacuum formation of coatings' comprises the following:

- physical vapor deposition (PVD);
- low-pressure chemical vapor deposition (LP-CVD))
- plasma-enhanced CVD (PECVD).

Table 1 summarizes the advantages and disadvantages of various methods of formation of coatings.

Table 1. Advantages and disadvantages of various methods of formation of coatings.

No.	Method	Advantages	Disadvantages
1	PECVD	1. Treatment of numerous simple elements, alloys, composite and vitreous materials; 2. Creation of coatings which microstructure can be varied in a wide range from amorphous to mono- and polycrystalline; 3. High rate of coating deposition. 4. Possibility to deposit coatings on complex-shaped products. 5. This equipment is compatible with other kinds of vacuum equipment.	1. High temperatures at which coatings are formed. 2. Some vaporized materials may be expensive and environmentally hazardous (for example, explosive hazard and toxicity of hydrogen as a carrier gas) or chemically unstable. 3. Presence of large quantities of unreacted components. 4. Sophisticated regulation and control due to a great number of parameters. 5. Incomplete decomposition of the original material may lead to presence of unpredictable contaminants in the coating.
2	Electron beam vaporization	1. High rate of coating deposition 2. Possibility to create thick coatings (up to 200 micrometers). 3. High purity (minimal content of impurities in finished coatings).	1. Uneven thickness and uneven stoichiometry in case of complex-shaped products. 2. Low deposition rate due to small volume of the chamber.
3	Laser ablation	1. Possibility to deposit coatings on complex structures. 2. High purity (minimal content of impurities).	1. Implementation complexity. 2. Low deposition rate.
4	Thermal vaporization in vacuum	1. High rate of coating deposition 2. Possibility to create thick coatings	1. Insufficiently dense structure of the coatings. 2. Poor mechanical properties of finished films.
5	Cathodic arc vaporization	1. Vaporization/ Pulverization of any conductor materials 2. The vacuum arch plasma is a valuable tool for ionization of both, the vaporized material and the reactive gas in case of a reaction. 3. The ions of the vaporized material can be additionally accelerated via application of voltage. 4. Low energy losses via radiation in case of cathodic arc. 5. Use of planar sources of vaporized/ pulverized materials.	1. Presence of droplets in the flow of vaporized material and, consequently, their presence in coatings. 2. A limited range of materials (only conductor materials can be vaporized/ pulverized) 3. Large energy losses through radiation (anodic arc).
6	Magnetron sputtering	1. It is possible to vaporize pure elements, alloys and composite materials. 2. The vaporized/ pulverized target is suitable for formation of even coatings with the same composition during a long period of time. 3. It is possible to use flat sources of vaporized material as well as sources shaped like cylinders or rods. 4. During vaporization the energy losses via radiation are small. 5. The source and the treated surface can be placed at a rather small distance from each other. 6. Use of planar sources. The vacuum chamber can be small.	1. Low vaporization rate (if compared with thermal vaporization) 2. In order to obtain even coatings it is necessary to use mobile equipment due to certain specific features of the flow of vaporized material. 3. A sophisticated process of fabrication of targets. 4. A large portion of the energy, transferred by charged particles to the surface, is transferred away via cooling. 5. In certain cases plasma activates the contaminants that are inevitably present in any gas or any vacuum, and this activation may influence the composition and functional properties of coatings. 6. One should carry out an accurate monitoring of the feeding of the reactive gas.

Research carried out in "Moscow Power Engineering Institute" [26] and also other authors [27, 28] have shown that the ion-plasma deposition technologies allow to obtain coatings (PVD) that are not inferior to those obtained with the use of traditional thermal-chemical technologies (CVD). Ionic-plasma deposited coatings efficiently increase the durability of equipment and in particular the erosion and corrosion resistance of rotating blades of turbines.

The cost-effectiveness of ion-plasma coatings is due to rather low consumption of coatings' components, and although their mass and volume are less by orders of magnitude than the mass and volume of the protected material, they increase the service life of the latter in several times.

The main advantages of the ion-plasma coatings enabling their use for increasing the durability of the components of turbines are the following:

1) high energy of the deposited particles : from 10 eV to 1000 eV and possibility to have control over this energy and therefore to have control over the properties of coatings;
2) low temperatures at which coatings are formed: 230-500 °C;

3) synthesis of new extra-strong materials with unique physical and mechanical properties (nitrides, carbides, carbon nitrides of chemical elements with high melting points Ti, TiAl, Cr);
4) formation of universal composite coatings with required functional properties.

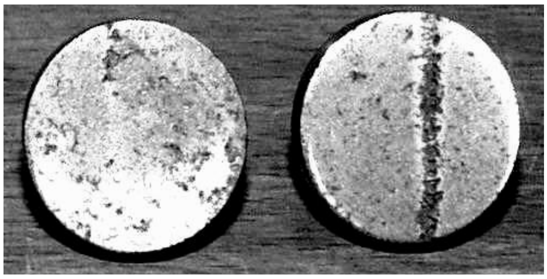
The ionic and plasma deposition technologies are environmentally friendly and endow work surfaces with unique physical and chemical properties; therefore their large-scale implementation across the turbine manufacturing industry is an urgent challenge.

METHODS TO INCREASE THE EROSION RESISTANCE OF MATERIALS USED FOR MANUFACTURING OF BLADES

Multi-year research of vacuum deposited ionic-plasma coatings that was conducted by "Moscow Power Engineering Institute" [21, 29-30] shows their high efficiency when seeking to improve both erosion and corrosion resistance of the last-stage blades of powerful turbines.

Nitrides, carbides and carbonnitrides of Ni, TiAl and Cr and in particular $TiAl_xN_y$ -based and CrN-based protective multilayer coatings have good prospects for their future use as erosion-resistant coating materials. The erosion resistance of such coatings depends to a large extent on their physical, chemical and mechanical properties, as well as on the conditions at which they were formed.

The analysis of the results of the research shows that such composition of multilayer ionic-plasma deposited coatings is highly efficient because these coatings possess universal properties and enable increasing both erosion and corrosion resistance of blade materials, while the fatigue resistance remains high. Being only 10÷20 micrometers thick such coatings increase the incubation period (the period before mass loss begins) of the erosion of the work surface of a loaded element by a factor of 2 or 3. Figure 1 presents samples of 20Kh13 blade steel with multilayer coatings composed of alternating layers of Ti and TiN obtained with the use of equipment and technologies developed by the "Moscow Power Engineering Institute".



a) b) c) d)

a) TiN coating; c) TiN-based multilayer coating; b) and d) uncoated 20Kh13steel
Figure 1 – Photos of samples of20Kh13blade steel with vacuum deposited ionic and plasma coatings after erosion resistance tests
(impact speed: 250 meters per second; droplet diameter: 800 micrometers)

If compared with single-layer coatings, the advantage of multi-layer coatings consists in certain conditions multi-layer coatings combine various functional properties that meet even contradictory requirements.

Although corrosion resistance of a multilayer coating can be ensured via creation of a sublayer of a uniform corrosion-resistant material having a certain minimal thickness as it is shown in [31], maintaining necessary resistance of the coating to the droplet impact erosion is rather difficult and the solutions depend on numerous factors including mechanical properties of the substrate material. As it was shown in [32],if the droplet load varies with time, the structure and microhardness of the subsurface layer of the substrate are affected and the undergone changes cause deterioration of this layer. A coating can inhibit this process due to high rigidity and significantly greater plasticity. However, in this case the most vulnerable point are the possible looseness of the coating due to uneven deformations of both the coating and the protected material (plastic flow of the material protected by a rigid coating) and the deterioration of the substrate that reduces the service life of the coating.

In the context of erosion resistance, the most vulnerable place is the boundary between the coating and the subsurface substrate layer: at this place the strength of the 'coating–substrate system' is to a large extent determined by the quality of adhesion, overall thickness of the coating, thickness of the coating's layers and their acoustic properties. Designers should also take into account that the 'coating-substrate system' is the place of generation of waves that are there after reflected from the layers of the coating and interfere leading to concentration of energy in small volumes inside the coating.

The hardness of the 'coating-substrate system', morphology of the subsurface layer, various defects on the surface and inside the coating also significantly influence erosion resistance. In order to ensure sufficient adhesion at the boundary between the coating and the subsurface layer of the substrate one can create a single-component or a multi-component diffuse transition layer, for example, via plasma-chemical modification or via modification of the subsurface layer with the use of high-energy ions so that the properties of the material would smoothly change in the depth range from several tens or hundreds of micrometers to zero, i.e. up to the surface.

At present a large number of publications are devoted to modification of properties of near-surface layers of blade materials causing structural changes resulting in increase of microhardness and wear resistance although the properties and structure of the protected substrate material remain unchanged [33-35].

The depth of the modified layer is determined on the average size of the impinging droplets of the fluid so that the hardness would increase; as the structure becomes denser, the corrosion is reduced.

According to the proposed concept of increasing erosion resistance, first of all it is necessary to modify the protected surface in such a manner that the structure of the subsurface layer would become denser and therefore the gradient of the hardness would increase and the defects would be repaired. In future one should further optimize the modified surface, i.e. create a structure of layers of ionic-plasma deposited coatings that are composed of hard wear-resistant layers of nitrides and carbides of metals (Me_xN_y, Me_xC_y) alternating with layers of pure metal (Me) that reduce internal stress, as it shown on the Figure 2.

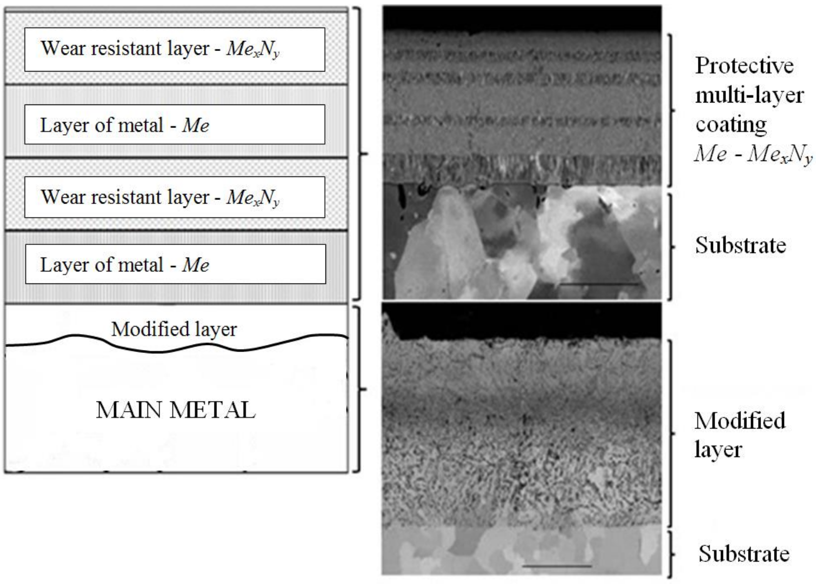


Figure 2 – Structure of a protective coating (with modified surface of the substrate)

CONCLUSIONS

The trend towards development of super-long last-stage blades of steam turbines will lead to an increase of circular speed of rotating blades in the peripheral parts of turbines up to 800 meters per second thus intensifying the erosion of the entering edges; therefore the challenge of developing new methods for improvement of the erosion resistance of blade materials has raised to a new level of urgency.

The erosion resistance of components of power equipment can be improved via creation on their surfaces of protective multifunctional ion-plasma deposited coatings in combination with modification of the protected surface leading to a denser structure of the subsurface layer and therefore a gradient increase of its hardness (protection against droplet impact erosion) and repairing defects that occur in this layer (protection against corrosion, raising the fatigue limit).

In order to implement this approach to improvement of erosion resistance, materials and technologies must be chosen on the analysis of the operating conditions, study of mechanical properties of said materials and results of corrosion, erosion and fatigue tests of coated materials with modified surface.

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