Increment of steam turbine blades service life by means of erosion-resistant plasma coating deposition with meso-ordered structure

V E Bogdanovich and M G Giorbelidze

Abstract. Main reasons and wear mechanism of steam turbine blades have been examined. Efficient recovery method of steam turbine blades allowing to increase their service life and enhance greatly service life of power units have been suggested. Materials to deposit coating layers have also been selected and deposition technology have been developed. Structure, porosity, micro-hardness, adhesion strength, erosion resistance and heat resistance of deposited coating have been researched. Suggested method can be used both for deposition of a coating on new turbine blades and for recovery of worn surfaces without overhaul of a turbine due to applying of a mobile compact plasma unit of in-house design. Composition of the coating featuring meso-arranged structure during deposition process greatly increases most operational performances of the whole ‘coating – substrate’ system.

1. Introduction
Main reason of exhaust of service life of power units of most heat-power stations is connected with erosion and contact wear of different surfaces of a turbine because of high loads, high rotation rates and impact of fast steam gas flows including a lot of moisture drop phase at its last stages [1,10,12-14]. In recent two decades, it is noted that while performing scheduled repair works, there is a persistent tendency of parts wear increase of steam turbines, especially leading edges of blades. It is stipulated for alternate operational modes of heat-power stations because of necessity of more economy mode of their operation. In spite of considerable experience of designing and operation of moist-steam turbines in Russia and abroad and numerous theoretical and experimental research, the problem of efficient protection of blades of a low-pressure cylinder at the turbine last stages from considerable erosion during operation comparable with technological lifespan is apart from its solution. Solution of the problem is carried out due to constructively - technical measures when designing, development and operation of steam turbines to decrease specific content, dispersity and normal velocity component of the drop phase hitting blade surface. Research of physics and dynamics of development, movement and hit of drop phase on the surface, research of mechanisms of initiation and development of surface erosion, erosion resistance of structural materials and development of methods of surface hardening along with methods of repair and recovery of structural components after erosive damage are also considered.
2. Problem solving method

Method of performance restoration of power units assumes essential economic expenditures because of dismantling and transportation of units when replacing old items that depleted their service life with new ones [1,2]. This, in turn, results in additional economic wastes because of lengthy downtime of equipment up to finishing of overhaul. To recover surfaces of worn parts of power units there exist different methods such as vacuum ion-plasma deposition, high-speed deposition and others. However, most of these methods are ineffective or their application is not admissible in heat-power station conditions [3-7].

Specialists of Research institute of Technology and quality problems of Samara National Research University named after academician S. P. Korolyov have discovered an opportunity to recover and to increase essentially service life of power unit parts by means of plasma deposition method [1]. Besides, the process of surface hardening and recovering of sizes of blades, shafts and other parts can be carried out directly at heat-power stations without total unit dismantling.

It is generally known, that blades of the last stages of steam turbines of heat-power stations operating in moist steam environment are subjected to erosive wear as a result of impact and cavitation action of the environment, especially the surface of the leading edge [8].

At the surface of the leading edge of newly manufactured blades there are soldered hard-alloy stellite plates providing protection from erosive wear. After long-term operation of blades, in the spots of plate locations erosive wear arises. They look like cavities, superficial and deep grooves, breakoff of stellite plates and turbine blades damage are also possible (Figure 1).

To repair leading edges of such blades it is usually necessary to dismantle the turbine and soldering of new stellite plates. It is exceptionally labour intensive process, as it requires matching and soldering of a great number of such plates to each blade maintaining given temperature mode when soldering.

Authors of this article have substantiated and proved in practice more than once necessity of application on recoverable items plasma coatings protecting expensive parts of units from wear and destruction arising as a result of deep damage in structural material. It should be noted that it is prospectless to find ideally resistant coating material in view of economic inexpediency and technical impossibility.

The task of the coating is to protect structural material over the time of overhaul period of unit operation when permissible wear of the coating is taking place. Technology's task is to provide coating recovery without considerable thermal influence on structural material happening during welding, overlaying welding, soldering, etc., moreover, less expensive cost of works in comparison with the cost of replacement of a set of used parts with new ones. A protective coating is to have substantially smaller
wear rate then the stellite protection used, and coating thickness is to provide operating time much greater than existing stellite protection of 2 mm thickness.

Analysis of available research data on mechanisms of erosive fatigue damage of homogeneous materials, stellite and plasma coatings, as well as carried out theoretical and experimental research allowed to explain significant difference of their wear mechanisms. One of the essential results of such research is the fact that obtaining coatings with the structure having location of intercrystalline boundaries mainly along the outer surface of the item, it greatly increases majority of performance characteristics of the whole ‘coating-substrate’ system [1]. It has been found that such a structure called meso-arranged according to the authors [9], could be obtained by means of plasma gas-thermal deposition from most powder materials due to the choice of deposition mode [9].

3. Problem solving method

To choose the composition of erosion resistant coating for blades protection of steam turbines, nickel – aluminum, nickel – cobalt – chromium – aluminum – yttrium, titanium – nickel, chromium carbide – nickel systems and their combinations were researched. The subjects of inquiry were the structure, porosity, phase composition, micro-hardness, adhesion strength, heat resistance and erosion resistance of deposited coatings.

Metallographic research were carried out using cross sections of coatings. Coating samples were filled in special rings, and treated by the buffing and grinding machine Gripo 1V. Microstructure research was carried out using special equipment complex for metallographic analysis including a metallographic microscope and software to provide image analysis based on the computer Image Expert Pro 3.0 Professional. Application of this software allows to determine porosity of deposited layers. Research of phase composition of the coating were carried out by means of scanning electron microscope TESCAN Vega SB.

Micro-hardness of phase terms of coatings was determined under indentation load 0.2 and 0.49 N at 100 points for a length of 10 mm every other (80-100) μm. According to measurement results, values distribution histogram of layer micro-hardness in coordinates ‘micro-hardness – number of prints’ in percent were built. Measurement results and well known research data on micro-hardness of phase terms allows to evaluate percentage and phase distribution in the coating, as well as the conservation degree of a carbide phase under coating deposition, which can partly recover under isothermal particle deposition by a plasma jet. Research of adhesion strength were carried out applying glue method according to State Standard 9.304 – 87 ‘Gas-thermal coatings. General requirements and inspection methods’. To carry out research for heat resistance special equipment was used. Qualitative method was used. The samples were heated with after air-cooling, and arising stresses and strains were not evaluated. Number of cycles before peeling or destruction of the coating were determined. The sample with coating was secured in shunts. Heating was provided by a current transformer up to the temperature 1000 °C. The temperature was measured by means of a potentiometer and a thermocouple. Potentiometer output was connected to the automatic control unit, which maintained sample temperature within the prescribed limits by means of a contactor. Heating rate was 10 °C per second, it was adjusted by the autotransformer, and number of cycles was recorded by the counter. Tests were carried out in automatic mode keeping the prescribed temperature for 20 seconds. Checking took place every 20 cycles up to destruction or peeling of the coating.

Tests for erosion resistance carried out at special testbed allowing to simulate conditions of interaction of drops of liquid with the surface of structural material and protective coatings samples. When researching erosive wear process of the material, the value of mean erosive wear of the material or coating depending on specific weight of drops per a unit of eroded surface was measured.
Research for choosing coating composition was carried out using samples. For each of researched materials the mode was determined using mathematical modelling. In this mode powder particles of deposited materials of narrow fractions are accelerated by plasma jet during coating layer formation, they are heated up to the temperature when only particle surfaces are melted, but the deposited particle itself is deformed in a cluster of a meso-arranged coating. Meso-arranged coatings have layer structure consisting of separate disk-shaped clusters oriented along the surface of protected basic material, vertical and horizontal boundaries, as well as micro-cavities located within vertical boundaries between adjacent clusters. Thickness of a separate disk-shaped cluster is from 2 to 10 micrometers μm, it is several times less than characteristic horizontal dimension. Boundaries of such structure are limited by the surface of other crystallites in a vertical direction, as a result, closed porosity type is developed that prevents penetration of chemically active components to the basic material. As mentioned before, we have established that the coatings with meso-arranged structure having intercrystalline boundaries mainly along the outer surface of an item have higher performance characteristics.

Research of the coating structure deposited under strict conformity of the deposition mode of a disperse fraction of the deposited material and improvement of the powder feed system has shown that we are able to form cluster meso-arranged structure from powders of all researched materials.

Results of testing for adhesion strength by glue method have confirmed that cohesive strength of coatings reaches (36 – 40) MPa, and it exceeds adhesive strength. Coating porosity is (2 – 5) %, heat resistance of coatings exceeds 200 cycles at the mode (20 – 1000) °C. Determining factor for choosing composition of deposited coating were the test results on erosion resistance. Research of erosion resistance of plasma coatings has shown that the coating with composition Ni-Co-Cr-Al-Y + CrC-Ni in conditions of the test by the drops \( d_k = 400 \) μm at speed \( V_k = 25 \) 0 m/s has provided better protection than stellite. Under drop load \( 5 \times 10^4 \) kg/m² coating (worn about 30%) has shown erosion rate 1.4 times as less than stellite.

For deposition of the given coating, two materials were used: powder Ni-Co-Cr-Al-Y fraction (60 – 80) μm and powder CrC-Ni fraction (40 – 60) μm. Chemical composition of the powder: Ni – basis, Co – 21,3 %, Cr – 17,4 %, Al – 14,1 %, Y – 0,34 %. Powder deposition Ni-Co-Cr-Al-Y was carried out at the design mode: current strength 380 A, voltage (50 – 52) V, deposition distance 120 mm, argon consumption 35 l/min, hydrogen consumption 3.5 l/min. Thickness of the deposited layer was (250-300) μm.

Powder CrC-Ni was deposited at the mode: current strength 420A, voltage (52-54) V, deposition distance 120 mm, argon consumption 35 l/min, hydrogen consumption 3.5 l/min. Thickness of the deposited layer was (150-170) μm. Chemical composition of the powder: Cr – 70 %, C – 9,7 %, Ni – 20 %, Si – 0,3 %.

Structure of the deposited meso-arranged coating Ni-Co-Cr-Al-Y + CrC-Ni is shown in Figure 2, table 1 displays main parameters of its layers. The coating has homogeneous, dense structure; peelings, cavities, cracks and other defects have not been discovered.
To repair, harden and recover turbine blades of heat-power stations without their dismantling we have developed mobile compact unit and deposition technology. The unit is fitted with plasmatrons [11], meter regulators, manipulators of in-house design. It is also fitted with computer control system for deposition process, which allows to deposit homogenous coating on the surfaces of complex geometry (blades) without labor-intensive dismantling of power turbines and other similar assemblies. Mobile unit consists of separate assemblies. It is delivered to a heat-power station in a truck body and mounted at the turbine hall during a shift. It should be noted that the units of such type are not manufactured at present. Development of stationary plasma rooms at locations of large-dimension assemblies are not economically profitable.

During deposition turbine rotor is set on special support-bearings by a beam crane of the machine shop, deposition area is enclosed by polyethylene foil shields to eliminate opportunity of contamination of neighboring workshop objects. Examination and preparation for deposition of worn blades of the last rotor stages assembled are to be done. Deposition is performed sequentially along the worn surface of each blade using special manipulator; travel from the deposited blade to the following one is done by means of the rotor movement (Figure 3).
Figure 3. Recovering of operating blades of a steam turbine of a heat-power station using method of plasma deposition by means of a compact unit: a – recovery process; b – rotor blade recovered with plasma coating.

The first work dealing with recovering of leading edges of steam turbine blades was carried out more than 20 years ago on the turbine PT60–130/13. The last, 30th blade stage was removed because of its accident wear. Between overhauls of the steam turbine PT60–130/13 its observed life was 186,000 hours. When examining, it was discovered that 90% of all the blades of the 29th turbine rotor stage had total lack of stellite plates, and the remaining 10% of blades had only separate pieces of plates. In all cases, it was mentioned occurrence of partial erosive damages of leading edges at the places where stellite plates lacked. To prevent further erosion wear of leading edges, blade surfaces were cleaned from the remaining plate fragments. Then applying plasma gas-thermal method, we deposited two-layer protecting coating and recovered initial blade geometry by means of mobile equipment (Figure 3a), moreover, turbine rotor was not dismantled (Figure 3b).

In 218,544 hours of observed life, during the next overhaul visual inspection of operating blades of the 29th stage of the turbine rotor was done. It was noted that over 32544 hours plasma coating operated successfully protecting structural material. Erosion was not discovered on the material surface of blades, wear took place along the coating. Outer layer of the plasma coating was worn on all the areas excepting ‘suction face’ of blades, but the first layer was not worn completely. There were no deep cavities and sharp projections typical for erosion wear of the material on the surface of the remaining layer. As a result, operating blades of the 29th stage continued operating as turbine parts up to the next overhaul.

After examination of the turbine in 248,142 hours, it was discovered that surfaces of the blades were smooth and without erosion wear marks of structural material as before where the coating was deposited. Areas of outer layer of the coating at ‘suction face’ of blades preserved and had the same state as during the previous examination, in the last repair period.

4. Discussion of results

Finally, plasma coating deposited on the blades of the 29th stage of the steam turbine rotor provided efficient protection of structural material of the leading edge from erosion wear and destructive effect of fast steam-gas stream for 62,142 hours of operation (life time 10 years). Leading edges of 27th and 28th stages of turbine rotor that operated without coating within the same observed life had considerable erosion wear. It should be noted that in comparison with stellite plates the coating has much better protective properties. Obtained results and practical experience on providing efficient protection of structural material of steam turbine blades of a
heat-power station for more than 62,000 hours do not have analogues in world practice due to using plasma coatings, so they are the pioneering ones.

Physical nature of such erosion resistance increase of plasma coatings in comparison with the material of blade base or stellite plates is connected in many respects with special meso-arranged structure of the coating that provides its damping on impact and another mechanism of micro-wear on erosion [1].

By now, works on deposition of erosion-resistant coating on two last stages (30 and 29 stages) have been completed on 9 turbines of different heat-power stations. Obtained beneficial results have predetermined for transition on more cost-beneficial operating procedure – on real situation, when during scheduled repair of the steam turbine without its dismantling, plasma coating is deposited to harden blade surfaces. Besides, cost of works does not exceed 10% of cost of a new blade set. During the next scheduled repair, blades with coating are examined, then the decision is made on coating recovery or extension of operation. The important condition on operation on real situation is absence of main material damages of a blade before coating deposition. Such damages being a concentrator of fatigue failure development will result in necessity of expansive replacement of an old blade with a new one. Obtained experimental results on operation mode on real situation prove possibility of service life increase of blades of 29th and 30th stages subjected to erosion wear in not less than 3 times.

Thus, developed technology of recovery and hardening of power unit parts applying plasma deposition allows to increase durability of power unit parts subjected to erosion wear in 3 times. It also decreases expenses on repair of separate parts and assemblies of power plants in dozens of times, reduces power equipment down time because of repair and failure in about 20 times, and reduces probability of man-caused impacts in case of equipment breakdown and failures.

Acknowledgement

The reported study was funded by the Ministry of Science and Higher Education of the Russian Federation.

References

[1] Barvinok V A 2005 Plasma in technology, reliability, resource Moscow: Science and technology publisher p 452
[2] Bobrov G V, Iljin A A and Spektr V S 2014 Theory and technology of formation of inorganic coatings Moscow: Alfa-M publisher p 925
[3] Hawking M 2000 Wasantasri V., Sidqi P. Metal and ceramic coatings: Preparation, properties and application Moscow: World publisher p 518
[4] Ryzhenkov V A 2000 State of the problem and ways to increase the wear resistance of power equipment of TPP Heat power engineering (№6) pp 20-25
[5] Lisyansky A S, Lisyansky A S, Tikhomirov S A, Simin O N and Chizhik T A 2005 Providing resistance to drop-impact erosion and fretting corrosion of steam turbine blades due to vacuum ion-plasma surface hardening Energomashinostroenie (№2-3) pp 43-53
[6] Smyslova M K 2004 Research and development of combined ion-plasma technologies that improve the performance properties of gas and steam turbine blades Vestnik UGATU. ( Vol.5 № 3(11)) pp 67-83
[7] Mann B S and Vivek Arya 2003 HVOF coating and surface treatment for enhancing droplet erosion resistance of steam turbine blades Wear (Vol. 254, Issues 7-8 DOI: 10.1016/S0043-1648(03)00253-9) pp 652 – 667
[8] Perelman R G and Pryakhin V V 1986 Erosion of steam turbine elements Moscow: Ehnergoatomizdat publisher p 184
[9] Barvinok V A and Bogdanovich V I 2012 Physical and Mathematical Simulation of the Formation of Mesostructure-Ordered Plasma Coatings Technical physics (Volume 57, Issue 2 DOI: 10.1134/S1063784212020053) pp 262 – 269

[10] Mann B S 2014 Water Droplet Erosion Behavior of High-Power Diode Laser Treated 17Cr4Ni PH Stainless Steel Journal of Materials Engineering and Performance (Volume 23, Issue 5 DOI: 10.1007/s11665-014-0927-6) pp 1861 – 1869.

[11] Barvinok V A, Bogdanovich V I and Dokukina I A 2014 Patent № 31897 RF MPK7 N05NS 1/26. Plasma torch for spraying metals and oxides applicant and patent holder: Federal state Autonomous educational institution of higher education "Samara state aerospace University named after academician S. P. Korolev (national research University)" (declared 21.11.2013, published 10.07.2014)

[12] Liu-xi Cai, Jing-ru Mao, Shun-sen Wang, Juan Di and Zhen-ping Feng Experimental investigation on erosion resistance of iron boride coatings for steam turbines at high temperatures Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology (Volume 229, Issue 5 DOI: 10.1177/1350650114557105) pp 636 – 645

[13] Pérez F J, Castañeda S I, Hierro M, Escobar R, Galindo J C and Sánchez-López S Mato 2014 Comparative Study of Micro- and Nano-structured Coatings for High-Temperature Oxidation in Steam Atmospheres Oxidation of Metals (Volume 81, Issue 1-2 DOI: 10.1007/s11085-013-9447-2) pp 227 – 236

[14] Shipway P H and Gupta K 2011 The potential of WC-Co hardmetals and HVOF sprayed coatings to combat water-droplet erosion Wear (Volume 271, Issue 9-10 DOI: 10.1016/j.wear.2010.12.058) pp 1418 – 1425