ISSN 2518-1483 (Online),
ISSN 2224-5227 (Print)

2022 • 1

ҚАЗАҚСТАН РЕСПУБЛИКАСЫ
ҰЛТТЫҚ ҒЫЛЫМ АКАДЕМИЯСЫНЫҢ

БАЯНДАМАЛАРЫ

ДОКЛАДЫ

НАЦИОНАЛЬНОЙ АКАДЕМИИ НАУК
РЕСПУБЛИКИ КАЗАХСТАН

REPORTS

OF THE NATIONAL ACADEMY OF SCIENCES
OF THE REPUBLIC OF KAZAKHSTAN

PUBLISHED SINCE JANUARY 1944

ALMATY, NAS RK

ҚАЗАҚСТАН РЕСПУБЛИКАСЫ
ҰЛТТЫҚ ҒЫЛЫМ АКАДЕМИЯСЫНЫҢ

БАЯНДАМАЛАРЫ **2022 • 1**

«Қазақстан Республикасы Ұлттық ғылым академиясының баяндамалары»
ISSN 2518-1483 (Online),
ISSN 2224-5227 (Print)
Меншіктеуші: «Қазақстан Республикасының Ұлттық ғылым академиясы» Республикалық қоғамдық бірлестігі (Алматы қ.). Қазақстан Республикасының Ақпарат және қоғамдық даму министрлігінің Ақпарат комитетінде 29.07.2020 ж. берілген **№ KZ93VPY00025418** мерзімдік басылым тіркеуіне қойылу туралы куәлік.
Тақырыптық бағыты: *өсімдік шаруашылығы, экология және медицина саласындағы биотехнология және физика ғылымдары.*
Мерзімділігі: жылына 4 рет.
Тиражы: 300 дана.
Редакцияның мекен-жайы: 050010, Алматы қ., Шевченко көш., 28; 219 бөл.; тел.: 272-13-19
http://reports-science.kz/index.php/en/archive

Типографияның мекен-жайы: «Аруна» ЖК, Алматы қ., Муратбаева көш., 75.

ДОКЛАДЫ **2022 • 1**

НАЦИОНАЛЬНОЙ АКАДЕМИИ НАУК
РЕСПУБЛИКИ КАЗАХСТАН

Доклады Национальной академии наук Республики Казахстан»
ISSN 2518-1483 (Online),
ISSN 2224-5227 (Print)
Собственник: Республиканское общественное объединение «Национальная академия наук Республики Казахстан» (г. Алматы). Свидетельство о постановке на учет периодического печатного издания в Комитете информации Министерства информации и общественного развития Республики Казахстан **№ KZ93VPY00025418,** выданное 29.07.2020 г.
Тематическая направленность: *биотехнология в области растениеводства, экологии, медицины и физические науки.*
Периодичность: 4 раз в год.
Тираж: 300 экземпляров
Адрес редакции: 050010, г. Алматы, ул. Шевченко, 28; ком. 219; тел. 272-13-19
http://reports-science.kz/index.php/en/archive

Адрес типографии: ИП «Аруна», г. Алматы, ул. Муратбаева, 75.

REPORTS **2022 • 1**
OF NATIONAL ACADEMY OF SCIENCES OF THE
REPUBLIC OF KAZAKHSTAN

Reports of the National Academy of Sciences of the Republic of Kazakhstan.
ISSN 2518-1483 (Online),
ISSN 2224-5227 (Print)
Owner: RPA «National Academy of Sciences of the Republic of Kazakhstan» (Almaty). The certificate of registration of a periodical printed publication in the Committee of information of the Ministry of Information and Social Development of the Republic of Kazakhstan **No. KZ93VPY00025418,** issued 29.07.2020.
Thematic scope: *biotechnology in the field of crop research, ecology and medicine and physical sciences.*
Periodicity: 4 times a year.
Circulation: 300 copies.
Editorial address: 28, Shevchenko str., of. 219, Almaty, 050010, tel. 272-13-19
http://reports-science.kz/index.php/en/archive

Address of printing house: ST «Aruna», 75, Muratbayev str., Almaty.

REPORTS OF THE NATIONAL ACADEMY OF SCIENCES OF THE REPUBLIC OF KAZAKHSTAN
ISSN 2224-5227
Volume 1, Number 341 (2022), 117-123 https://doi.org/10.32014/2022.2518-1483.140

UDC 620.19:621.31

M. Skakov[1], As. Zhilkashinova[2]*, I. Ocheredko[2], Al. Zhilkashinova[2]

[1]National Nuclear Center, Kurchatov, Kazakhstan;
[2]Sarsen Amanzholov East Kazakhstan University, Ust-Kamenogorsk, Kazakhstan.
E-mail: asssel2462@mail.ru

COMPUTATIONAL - EXPERIMENTAL METHOD OF FORECASTING THE LIFETIME OF CO-CR-Al-Y COMPOSITE COATINGS

Abstract. The article describes a magnetron method for applying a multilayer Co-Cr-Al-Y coating on a steel substrate. Studies of the erosion and corrosion resistance of steel samples and samples with coatings have been carried out. The finite element method simulated the operation of the turbine under the influence of abrasive particles. The erosive load on the turbine blades was modeled, based on the experimental data on erosion and corrosion resistance, the durability was estimated taking into account the zones of the most intensive wear of the blades. It is established that the blades have uneven wear. Calculations showed that the resource of turbines with coatings based on Co-Cr-Al-Y is two times higher than turbines made of 12X13 alloy.

Key words: coating, structural-phase state, blades of gas-turbine engines, magnetron, finite element method.

М.К. Скаков[1], Ас.М. Жилкашинова[2]*, Ал.М. Жилкашинова[2], И.А Очередько[2]

[1]Қазақстан Республикасының Ұлттық ядролық орталығы, Курчатов, Қазақстан;
[2] Сәрсен Аманжолов атындағы Шығыс Қазақстан университеті, Өскемен, Қазақстан.
E-mail: asssel2462@mail.ru

CO-CR-Al-Y КОМПОЗИТТІК ЖАБЫНДАРЫНЫҢ ҚЫЗМЕТ ЕТУ МЕРЗІМІН БОЛЖАУДЫҢ ЕСЕПТІК-ЭКСПЕРИМЕНТТІК ӘДІСІ

Аннотация. Мақалада болат субстратқа көп қабатты Co-Cr-Al-Y жабынының магнетронды әдісі сипатталған. Болат үлгілері мен жабыны бар үлгілердің эрозиялық және коррозияға төзімділігі бойынша зерттеулер жүргізілді. Соңғы элементтер әдісі абразивті бөлшектердің әсерінен турбинаның жұмысын модельдейді. Турбина қалақтарына эрозиялық жүктеме модельденді, эрозиялық және коррозияға төзімділіктің эксперименттік деректері негізінде пышақтардың ең қарқынды тозу аймақтарын ескере отырып, беріктікке баға берілді. Пышақтардың біркелкі емес тозуы анықталды. Есептеулер Co-Cr-Al-Y негізіндегі жабындары бар турбиналардың ресурсы 12х13 қорытпасынан жасалған турбиналарға қарағанда екі есе жоғары екенін көрсетті.

Түйін сөздер: жабын, құрылымдық-фазалық күй, газтурбиналық қозғалтқыштардың қалақтары, магнетрон, соңғы элементтер әдісі.

М.К. Скаков[1], Ас.М. Жилкашинова[2]*, Ал.М. Жилкашинова[2], И.А. Очередько[2]

[1]РГП на ПХВ «Национальный ядерный центр Республики Казахстан», Курчатов, Казахстан;
[2]НАО «Восточно-Казахстанский университет им. С. Аманжолова», Усть-Каменогорск, Казахстан.
E-mail: asssel2462@mail.ru

РАСЧЕТНО-ЭКСПЕРИМЕНТАЛЬНЫЙ МЕТОД ПРОГНОЗИРОВАНИЯ РЕСУРСА КОМПОЗИЦИОННЫХ ПОКРЫТИЙ CO-CR-Al-Y

Аннотация. В статье описан магнетронный способ нанесения многослойного покрытия Co-Cr-Al-Y на стальную подложку. Проведены исследования эрозионной и коррозионной стойкости стальных образцов и образцов с покрытиями. Методом конечных элементов смоделирована работа турбины под воздействием абразивных частиц. Смоделирована эрозионная нагрузка на лопатки турбины, на основании экспериментальных данных эрозионной и коррозионной стойкости производилась оценка долговечности с учётом зон наиболее интенсивного износа лопаток. Установлено, что лопасти имеют неравномерный износ. Расчёты показали, что ресурс турбин с покрытиями на основе Co-Cr-Al-Y в два раза выше, чем турбины из сплава 12Х13.

Ключевые слова: покрытие, структурно-фазовое состояние, лопатки газо-турбинных двигателей, магнетрон, метод конечных элементов.

Introduction. As is known, modern gas turbine engines operate at temperatures at which hot gases expand in the direction transverse to the rows of turbine blades. The use of thermal barrier coatings on gas turbine blades and surfaces such as shroud segments has been found to have a number of advantages [1-2]. By using thermal barrier coatings, higher operating efficiency can be achieved, since less cooling air is needed to maintain the temperature of the blade or shroud. In addition, the service life of the parts increases, since due to the heat-insulating effect that creates a thermal barrier of the coating, the intensity of the temperature change of the metal decreases [3-5].

Thus, the problem of erosion wear of turbines of compressors in chemical industries, and, consequently, their protection, is of particular relevance. In addition to the high cost of gas turbines, the costs are associated with frequent shutdowns of production for the period of repair and installation work. At the same time, the efficiency of the enterprise as a whole depends on the operation of such units [4-6]. A promising way to increase the resource of turbines is to apply protective coatings resistant to erosion and chemical decomposition to their surface. However, coatings also have a high cost. Turbine blades wear out unevenly during operation, due to which significant savings in coating material can be achieved. Increasing the resource of turbines by constructing an experimental calculation method will allow us to find the optimal combination of the composition of coatings and the gradient of its distribution over the surface of the blade. Solving this technical problem will increase the durability of the turbines and reduce the cost of protective coatings.

In [7-9], the problems of developing a technology for improving the strength and operational properties of coating materials for turbine blades are highlighted. Hardening is achieved by using a pulse mode of formation and directed modifying effect of refractory compounds with submicro- and nanocrystalline structure on the surfacing process, structure, physical, mechanical and operational properties of coatings made of metals and alloys. Of great importance are the development of new methods of influencing surfacing alloys and the integrated use of existing developments. The application of protective coatings can increase the durability of the part without significantly increasing their cost.

The search for new high-temperature coatings is primarily associated with the optimization of the chemical composition of new compositions, with the development and development of new technological processes based on the use of fundamentally new physical effects, as well as with the use of newly created coatings [10-12]. The basic system of heat-resistant coatings is Me-Cr-Al, where Fe, Co, Ni act as Me [20].

Achieving the required level of performance of the rotor blades of engines is due to the creation of not only a heat-resistant alloy, but also with a workable heat-resistant wear-resistant coating. Moreover, it is very important that, along with reliable corrosion protection during the entire service life, the interaction of the coating material with the base would not worsen the strength properties of the blade metal (especially fatigue and thermal fatigue strength) on the one hand, and on the other, that the processes of interaction of the coating with the gas medium and the base were predictable. Such forecasting is the basis for determining the assigned resource of the blades [12-15].

A large number of studies have been devoted to the study of these processes and the issues of forecasting the life of coatings [16-18]. Currently existing experimental and computational methods for determining the life of coatings have a number of disadvantages. Experimental methods are labor-intensive and require a lot of time and resources. The lack of a reliable and economical method for predicting the service life of coatings makes it difficult to determine the permissible service life of engines before major repairs and reduces the reliability of the operation of the blade apparatus.

The purpose of this article is to determine the possibility of increasing the working life of turbines by constructing an experimental-computational method that will allow finding the optimal combination of the composition of the coatings and the gradient of its distribution over the surface of the turbine blade.

Methods and materials. The objects of the study were metal samples of 12X13 steel and samples of the same steel with coatings of the Co-Cr-Al-Y system. Coatings were deposited by the magnetron method on the ion-plasma facility "National Research Tomsk Polytechnic University" [19], which was a vacuum chamber with two magnetron sputtering systems of an unbalanced type and an ion source with a closed electron drift. The vacuum chamber of the installation is a sealed volume with a diameter of 500 mm and a height of 300 mm, equipped with flanges of various diameters for connecting vacuum fittings, vacuum sensors and other necessary devices (Figure 1).

The gas supply and adjustment system is represented by precision Bronkhorst ELFLOW mass flow regulators with an adjustment accuracy of 0.01 ml/min. The temperature control of the samples is carried out by means of a chromel - alumel thermocouple (the measured temperature range is 200-1100°C).

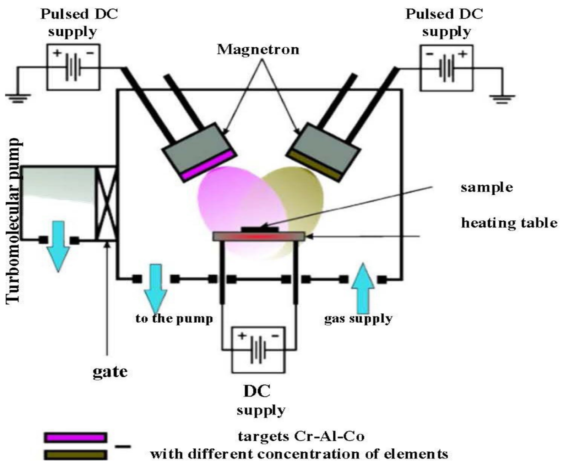


Figure 1 - Coating scheme

The following parameters were selected for spraying multilayer coatings with different concentrations of elements of the Co-Cr-Al-Y series:

- layer 1, the current magnetron Co/Al/Y – 0.5 A, voltage of magnetron Co/Al/Y – 450 V;
 current magnetron SG – 0.3 A, a voltage of the magnetron Cr – V. 320;
- layer 2, the current magnetron Co/Al/Y – 0.5 A, voltage of magnetron Co/Al/Y – 450 V;
 current magnetron SG – 0.6 A, the voltage of the magnetron Cr – 380.

The thickness of the layers was regulated by the spraying time. The coatings were deposited on a water-cooled substrate (Ta substrate holder).

The thickness of all synthesized Co-Cr-Al-Y coatings is 2±0.2 microns. To compare the structure, morphology and mechanical properties of multilayer Co-Cr-Al-Y coatings, films of 1, 2, 4 and 8 alternating layers were obtained [22].

The erosion load on the turbine blades was modeled using the finite element method, and durability was evaluated based on experimental data on erosion and corrosion resistance, taking into account the zones of the most intense wear of the blades. The simulation of the predominant wear of turbine blades was carried out by the finite element method. The modeling process is based on the assembly of the stiffness matrix (Dirichlet matrix) and mass. Boundary conditions are imposed on these matrices. Then a system of linear equations is assembled and solved by one of the known methods. The motion and heat exchange of the medium was modeled using the Navier-Stokes equations. To simulate turbulent flows, the Navier-Stokes equations were averaged by Reynolds, the effect of turbulence on the flow parameters on a small time scale, and large-scale time changes were averaged over a small time scale of the components of the gas-dynamic flow parameters were taken into account by introducing the corresponding time derivatives.

The method of studying erosion resistance is based on determining the mass loss of samples when blowing them with a gas-abrasive flow. Erosion tests of abrasive resistance were carried out on samples in the initial and heat-treated states at T= 20C0 in a 12G-53 jet-ejector type sandblasting unit. Test mode: abrasive material - electrocorundum 14A F 6; nozzle diameter 15.5 mm; air pressure p = 11 MPa; distance from nozzle to sample 310 mm; flow angle 30o. The samples were blown along the side surface of the sample. For studies of erosive wear, the average depth of erosion (E) was used as criteria, equal to the ratio of the decrease in the volume of the material to the area of the eroded surface and the volume of liquid (G/Ser) falling out per unit surface area.

The heat treatment of the coatings took place at the MILA-5000 installation (ULVAC-RICO (Japan), equipped with halogen IR lamps with a total power of 4 kW and a maximum radiation intensity in the range of 0.8 1.2 microns. The installation allows you to work in the temperature range from room to 1000°C with a maximum rate of temperature increase of 100°C/ min. The accuracy of temperature control and exposure time in the reaction chamber is ± 1°C and ± 1 sec, respectively. The sample is placed in a quartz holder. The intensity of the IR radiation is recorded by measuring the temperature using a chromel-alumel thermocouple placed directly on the sample. At this installation, work was carried out on heating samples at 400^0C, 800^0C and 1000^0C. The heats were carried out in a programmable mode with a preset output speed to the desired temperature, as well as during the transition from one annealing temperature to another. The annealing time at a given temperature or sequentially at several temperatures also took place in a programmable mode. The warm-up mode of the samples took place at a high vacuum ~ 1·10-7 mmHg: for 400°C - 10 minutes, heating lasted to the set temperature, holding for 10 hours, cooling was natural heat loss, the chamber was opened for sampling 1 hour after stopping the warm-up, when the temperature was below 100°C; for 800°C and 1000 0C: the same, heating for 20 minutes.

Corrosion resistance was determined by the gravimetric method to determine the mass loss of samples during their stay in the tested corrosive environment. The sample sizes were 50×20×2 mm. For the convenience of hanging, a hole was drilled in the samples. Before the tests, the surface of the samples was cleaned from solvent contamination, then sanded and polished, then degreased and etched. The samples prepared in this way were kept in a thermostat at a temperature of (100 ± 2)°C for 1 hour, cooled and weighed on analytical scales with an accuracy of 0.1 mg. The duration of the tests is 6 hours. Area of the samples was calculated with the formula:

$$S = 2\ [(a \cdot b - \pi \cdot d2/4) + \mathrm{h}\ (a + b + \pi \cdot d/2)],$$

where a is the length of the sample, m; b – width of the sample, m; h is the specimen thickness, m; d – diameter, m.

In gravimetric tests, the corrosion rate is characterized by a mass index of Km.

$$Km = m0 - m1/S\tau,\ \mathrm{g/(m2 * h)},$$

where m0 is the mass of the sample before the test, g; m1 – mass of the sample after the test, g; S is the initial surface area of the sample, m2; τ is the exposure time, h

Then counted the mass rate of corrosion depth, which characterizes pyroninophilia corrosion P:

$$\mathrm{N} = 8760\ Km/p \times 10\text{-}3\ \mathrm{mm/year},$$

where ρ is the material density, g/cm3; 8760 is the number of hours in a year.

Results and discussion. The simulation of the turbine operation was carried out by the finite element method. In the program of finite element analysis, the motion of a gas medium is modeled using the Navier-Stokes equations, which describe in a non-stationary formulation the laws of conservation of mass, momentum and energy of this medium. Calculations were carried out using a standard CFD solver, k-ε turbulence model.

At the same time, the entered geometric parameters had the following characteristics: the turbine diameter was 600 mm (Figure 2); the geometry of the blade profile had a standard radial turbine profile (Figure 3); the turbine was installed in the guide unit according to Figure 4.

The following turbine operating modes are selected: 1500 RPM, working medium - air, temperature - 400C0, abrasive material - electrocorundum, abrasive consumption 100 g/sec.

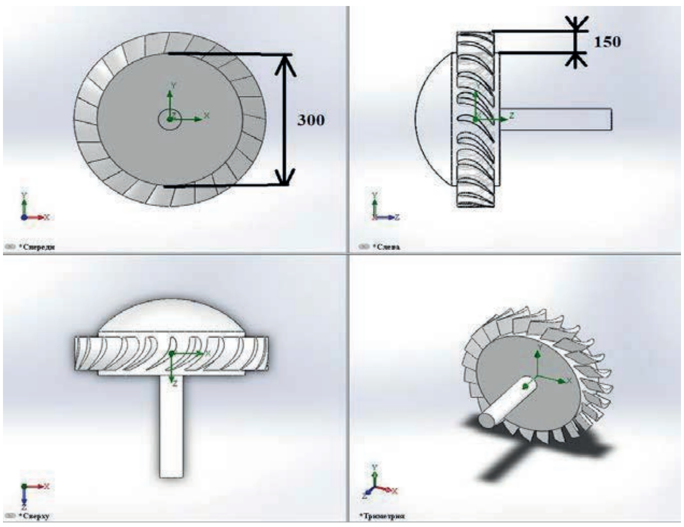


Figure 2 - Geometric parameters of a gas turbine

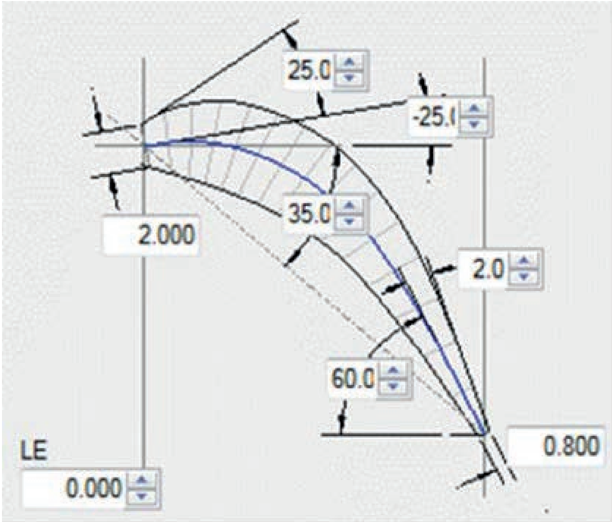


Figure 3 - Blade profile

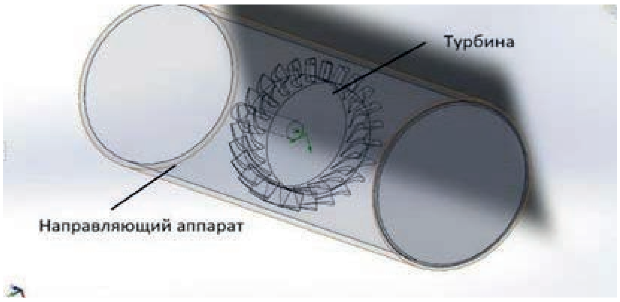
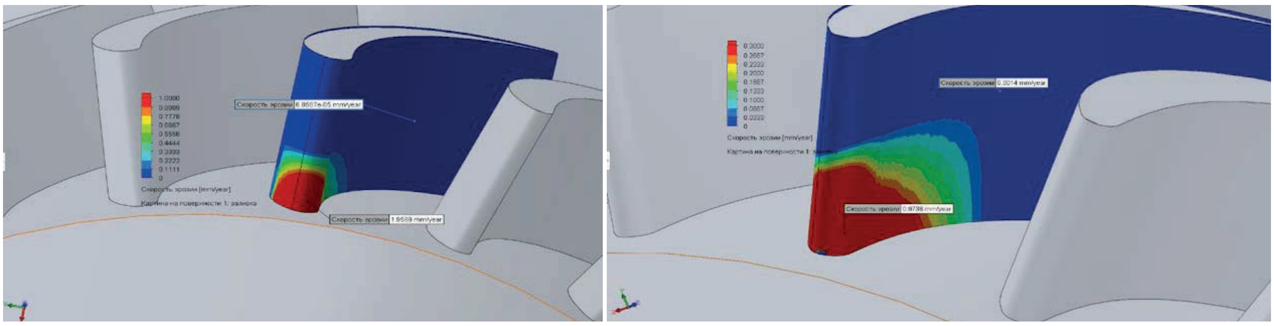


Figure 4 - Operation of the turbine in the guide unit

Experimental results on testing coatings for abrasion resistance allowed us to obtain the following data: in the initial state, a 4-layer coating of Co-Cr-Al-Y on a 12X13 steel matrix has an average value of 9.8598e-15 kg / (s *m2). After temperature treatment of these samples, the abrasive resistance had the following indicators: at 400^0C - 9.0122e - 15 kg / (s * m2); at 800^0C - 10.5897e - 15 kg /(s* m2); at 1000^0C - 10.9635e-15 kg /(s *m2).

Thus, experimental data showed a slight increase in erosion (abrasive) resistance (9.0122e-15 kg/(s*m2)) after heat treatment at 400^0C compared to the same samples in the initial state. The remaining samples at 800^0C and 1000^0C show a decrease in erosion resistance.

Figure 5 shows the results of forecasting the durability of blades with the values of abrasion resistance of steel 12X13 - 18.128e-15 kg/(s•m2) and blades coated with Co-Cr-Al-Y - 9.0122e-15 kg/(s*m2).



a b

Figure 5 - Prediction of the durability of blades with abrasion resistance values: a) steel 12X13 - 18.128e-15 kg/(s•m2) blades coated with Co-Cr-Al-Y - 9.0122e-15 kg/(s*m2)

In Figure 5, the zones with the maximum level of wear on the periphery of the blade are marked in red, it is established that the blades have uneven wear. The obtained data allows you to adjust the thickness of the coating. Table 1 shows the results of erosion and corrosion resistance, wear rate.

Table 1 - Comparative data of the main indicators of turbine durability based on 12X13 steel and coatings based on Co-Cr-Al-Y

Material	Unit of measurement	Steel 12X13	Steel 12X13 coated with Co-Cr-Al-Y
Erosion (abrasive) resistance	kg/(c*m2)	18.128e-15	9.0122e-15
Wear rate at the point of maximum erosion intensity	mm/year	1,9599	0,9738
Corrosion destruction	g/m3	1,96	1,92

From the comparative table it can be seen that the coated blades show up to two times higher erosion resistance and service life.

Conclusions. Multilayer coatings of Co-Cr-Al-Y on a 12X13 steel substrate were obtained by the magnetron method. For comparative analysis, heat treatment of these samples was carried out. Experimental results on tests for abrasion resistance allowed us to obtain the following data: in the initial state, a 4-layer coating of Co-Cr-Al-Y on a 12X13 steel matrix has an average value of 9.8598e-15 kg / (s * m2). After temperature treatment of these samples, the abrasive resistance had the following indicators: at 400^{0}C - 9.0122e - 15 kg / (s * m2); at 800^{0}C - 10.5897e - 15 kg /(s* m2); at 1000^{0}C - 10.9635e- 15 kg /(s *m2). A slight increase in erosion (abrasive) resistance was found (9.0122e-15 kg/(s*m2)) after heat treatment at 400 ^{0}C compared to the same samples in the initial state. The remaining samples at 800^{0}C and 1000^{0}C show a decrease in erosion resistance.

The operation of the turbine under the influence of abrasive particles is modeled by the finite element method. Based on experimental data of erosion and corrosion resistance, durability was evaluated taking into account the areas of the most intense wear of the blades. It is established that the blades have uneven wear. The intensity of erosion along the plane of the blade surface varies by an order of magnitude. These results make it possible to apply gradient coatings in thickness. At the same time, calculations have shown that the resource of turbines with coatings based on Co-Cr-Al-Y is about twice as high as turbines made of 12X13 alloy.

The process of erosive destruction is also aggravated by corrosion phenomena. The oxide film, which exists almost always on the surface of metals in gaseous media, especially at elevated temperatures, is destroyed by the flow of abrasive particles. At the same time, the metal surface is again subjected to oxidation, conditions for uneven corrosion destruction are created. For corrosive foci, erosive destruction occurs even more intensively, as the relief becomes more rough. The use of coatings based on Co-Cr-Al-Y can largely eliminate this problem.

Gratitude. *This research is funded by the Science Committee of the Ministry of Education and Science of the Republic of Kazakhstan (Grant No. AP08053322).*

Information about authors:

Skakov Mazhin – Doctor of physical and mathematical sciences, Academician of the National Academy of Sciences of the Republic of Kazakhstan; National Nuclear Center, Kurchatov, Kazakhstan, skakovmk@mail.ru, https://orcid.org/0000-0001-6836-1214;

Zhilkashinova Assel – doctoral student 3 years of study; Sarsen Amanzholov East Kazakhstan University, Ust-Kamenogorsk, Kazakhstan, https://orcid.org/0000-0002-3670-8444;

Zhilkashinova Almira – candidate of physical and mathematical sciences; Sarsen Amanzholov East Kazakhstan University, Ust-Kamenogorsk, Kazakhstan; almira_1981@mail.ru, https://orcid.org/0000-0003-0948-2280;

Ocheredko Igor– Do Research Fellow, NPLIT; Sarsen Amanzholov East Kazakhstan University, Ust-Kamenogorsk, Kazakhstan; egor007kz@mail.ru, https://orcid.org/0000-0001-8012-8589.

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БИОТЕХНОЛОГИЯ

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ФИЗИКА

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ISSN 2518-1483 (Online),
ISSN 2224-5227 (Print)

http://reports-science.kz/index.php/en/archive

Редакторы: *М.С. Ахметова, А. Ботанқызы, Д.С. Аленов, Р.Ж. Мрзабаева*
Верстка на компьютере *Г.Д. Жадырановой*

Подписано в печать 10.03.2022.
Формат 60х881/8. Бумага офсетная. Печать - ризограф.
9,0 п.л. Тираж 300. Заказ 1.

Национальная академия наук РК
050010, Алматы, ул. Шевченко, 28, т. 272-13-19