СТРУКТУРОУТВОРЕННЯ. ОПІР РУЙНУВАННЮ ТА ФІЗИКО-МЕХАНІЧНІ ВЛАСТИВОСТІ

STRUCTURE FORMATION. RESISTANCE TO DESTRUCTION AND PHYSICAL-MECHANICAL PROPERTIES

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THE INFLUENCE OF HEAT TREATMENT MODES ON THE STRUCTURE OF PROTECTIVE COATINGS

Purpose. *Increasing the durability of ГТК-10І hollow working blades due to double-sided protection of their profile part.*

Research methods. *Microstructure studies were carried out on microsections under a "Neophot-2" microscope and a "Stereoscan" microscope-analyzer. Microhardness was measured with a ПМТ-5 device. Short-term strength tests (GOST 1497-61, GOST 9651-61, GOST 1497-84) were carried out on standard cylindrical samples (diameter of the working part 5 mm, length 25 mm) at temperatures of 200, 800, 900 and 1000 °C on a УМЕ-10ТМ brand tensile machine. Long-term strength tests (GOST 10145-81) were performed on standard cylindrical samples at temperatures of 800, 900, 10000 °C and corresponding loads of 600, 400, 180 MPa on the AIMA-5-2 machine by uniaxial stretching of samples under constant load. Comparative experimental studies of high-temperature corrosion of alloys were carried out in synthetic ash using a method widely used in the industry. For corrosion tests, standard cylindrical samples (diameter ∅10 mm, length l = 12 mm) were used, on which, after preliminary degreasing, measurement and weighing on an analytical balance with an accuracy of (± 0.0005 g), synthetic ash in an amount of 12 mg / cm² was applied to their surface, simulating the combustion products of gas turbine fuel, which were placed and kept in a furnace on a platform made of refractory material in an air atmosphere.*

Results. *The influence of double-sided protection of the profile part of the working hollow blades of ГТК-10І was studied. It was shown that the formation of the coating is most effectively carried out at a temperature equal to or higher than the peritectic reaction temperature (≈1130 °C). It was established that the strength characteristics of superalloys when using the complex protection technology at temperatures of 800 and 850 °C do not decrease. It was shown that at relatively lower coating formation temperatures (1080 °C, 4 hours), the structure of the slip coating is significantly different from similar ones with a heterogeneous structure and fully corresponds to the classical RT-22A type. It was established that the predicted service life of the working blades increases by 10 thousand hours when using their double-sided protection using the complex technology.*

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Scientific novelty. *The obtained results make it possible to evaluate the processes occurring during coating application and blade operation and to establish the relationships between the thickness, kinetics and type of coating and the corrosion rate.*

Practical value. *The obtained results allow us to recommend developed coatings and application technologies to increase the strength characteristics and durability of products.*

Key words: *nickel-based superalloys, protective coating, coating structure, high-temperature corrosion, strength.*

Introduction

Protective coatings are designed not only to increase the operating temperatures of turbine blades, which are determined by the heat resistance of the alloys used for their manufacture, but also to increase the service life and reliability of the blades [1,2]. They have been used for more than 50 years. At the first stage, aluminide coatings were most widely used. Simple aluminizing of the working and guide blades of turbines allowed to increase the service life of gas turbine engines by approximately two times at a temperature of 850 °C [3,4]. However, these coatings are effective only in such typical corrosion as high-temperature oxidation due to the formation of a barrier layer of aluminum oxide. The use of low-grade fuel sharply reduces their efficiency.

Aluminide coatings doped with chromium, silicon, tantalum, niobium and other elements [5–7] have higher corrosion resistance compared to simple alithization, and also surpass them in thermal stability, plasticity and thermal stability strength. They are applied to the blades by various methods: diffusion (in powders with halide activators and in vacuum), slip, metallization, etc. Their thickness is within 40...100 microns. These coatings are effective when used in gas turbines with high-quality fuel. Under conditions of intense oxysulfide corrosion, their service life is short, since nickel intermetallics are unstable in contact with sodium sulfate and in its mixture with sodium chloride [8].

Aluminide coatings with a sublayer of precious metals (for example, platinum, rhodium) have become widespread abroad. These include such coatings as LDC - 2, RT - 22, RT - 22A, RT - 44, etc. They are characterized by high resistance to oxysulfide corrosion [9]. The thickness of these coatings is 70...80 μm, the base is NiAl, containing platinum aluminide $PtAl_2$.

Since the LDC-2 coating is characterized by porosity of the platinum layer, the possibility of concentration of contaminants at the platinum-substrate boundary, improved coatings based on them JML – 1 and JML – 2 [8, 9] have been developed. The platinum layers included in their composition are formed from molten salts.

Along with aluminide coatings, silicide coatings are also used. They are used mainly in low-power turbines with an operating temperature of up to 730 °C. They are characterized by high fragility of the silicide layer, low melting point (985 °C) of the eutectic formed by nickel silicides, poor thermal stability, and deterioration of the mechanical properties of the base metal due to the diffusion of silicon into it. In this regard, they are modified with chromium and tantalum [10].

Purpose

The main goal of the work was to increase the durability of the ГТК-10І hollow working blades by providing double-sided protection of their profile part.

Material and research methods

The development of nickel-based cast heat-resistant alloys is primarily due to the fact that, in comparison with deformed superalloys, they can achieve a greater strengthening effect due to the γ′- phase and carbides, and higher structural stability. Their diversity is associated with the level of operating temperatures and the requirements imposed on the properties of alloys at these temperatures (in particular, long-term strength, corrosion resistance). An important advantage of materials of this class is also the ability to cast thin-walled cooled blades of complex configuration from them, which are practically impossible to manufacture by forging and stamping methods. The use of cast superalloys for gas turbine engine (GTE) blades was largely facilitated by advances in the development of ceramic materials, equipment and equipment that allow castings with cooling channels to be obtained. For stationary gas turbines, heat-resistant corrosion-resistant alloys based on nickel ЭП-539ЛМ, ЧС-70ВІ, as well as alloys developed by National University Zaporizhzhia Polytechnic – ЗМІ-3 and ЗМІ-3У instead of imported alloys IN-738 have become widely used. They are used for the manufacture of working blades of gas turbines of the ГТК-10І unit.

The chemical composition of the studied heat-resistant alloys is given in Table 1.

Table 1 – Chemical composition of the studied cast nicke-base superalloys

Alloy grade	Element content, % by mass													
	C	Cr	Co	Al	Ti	Mo	W	Nb	Ta	Hf	Re	Ru	Zr	B
ЗМІ-3	0,1	13	5,5	2,9	4,9	1,8	4,5	-	-	-	-	-	-	-
ЗМІ-3У	0,1	13,	5,0	3,4	4,8	0,9	7,3	-	-	-	-	-	-	0,01
ЧС70	0,1	15	10	2,8	4,6	2,0	5,5	0,2	-	-	-	-	0,05	0,02
IN-738	0,1	16,	8,5	3,4	3,4	1,7	2,6	0,9	1,7	-	-	-	0,05	0,01
ЕП-539	0,1	18,	19,	3,0	3,0	4,2	-	-	-	-	-	-	0,05	0,01
EI-929	0,1	15	17	4,7	3,5	5,0	-	-	-	-	-	-	0,02	0,03

To protect the outer surface of the studied samples and working blades, condensing coatings developed by the E.O. Paton Institute of Electron-beam Technology are used, which are applied on a vacuum electron-beam installation УЕ-175М. The compositions used in the studies of electron-beam coatings (EBC) are presented in Table 2.

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Table 2 – Chemical composition of electron beam coatings

Coating brand	Element content, % by mass			
	Co	Cr	Al	Y
СДП-11А	basis	26…28	4,5…6,5	0,2…0,6
СДП-8	basis	25…28	9…11	0,2…0,6

After spraying, the first level of diffusion annealing is performed at a temperature of 1030...1130 °C, 2 hours in an electrothermal vacuum furnace of the type СШВ 8.12/13 ЕМ1 or "Schmetz". Before the second level of heat treatment, strengthening shot blasting with glass balls of 170...200 μm in size is performed on a shot blasting unit УДМ-2.

Protection of internal cavities of samples and hollow working blades of GTP is performed using technology developed by National University Zaporizhzhia Polytechnic.

The compositions of the applied suspension coatings used are presented in Table 3.

Table 3 – Chemical composition of diffusion coatings

Coatings	Element content, % by mass				
	Cr	Al	Si	Ti	Fe
Al-Si	-	80…88	12…20	-	-
Cr-Al-Si	8…10	70…80	10…12	-	-
Cr-Al-Si-Ti	16…25	65…72	6…10	1…5	-
Cr-Fe	70	-	-	-	30

Microstructure studies were carried out on microsections under a microscope "Neophot-2" and a microscope-analyzer "Stereoscan". Microhardness was measured with a ПМТ-5 device. Phase composition and lattice periods of the main components – on ДРОН-1 diffractometer in copper Kα radiation. The content of chemical elements - on a scanning electron microscope REM-106I.

Short-term strength tests (GOST 1497-61, GOST 9651-61, GOST 1497-84) were carried out on standard cylindrical samples (diameter of the working part 5 mm, length 25 mm) at temperatures of 200, 800, 900 and 10000C on a УМЕ-10ТМ brand tensile machine. Long-term strength tests (GOST 10145-81) were performed on standard cylindrical samples at temperatures of 800, 900, 10000C and corresponding loads of 600, 400, 180 MPa on the AIMA-5-2 machine by uniaxial stretching of samples under constant load. The relative elongation of the samples was recorded using mechanical strain gauges. At each load level, 3-5 samples were tested.

To assess the degree of reduction in the strength characteristics of the studied alloys as a result of prolonged thermal action at temperatures of 8500 and 9500 °C with different aging bases of 1000, 3000, 5000 hours, additional tests of samples were performed in accordance with the above-mentioned standards.

Research results and their discussion

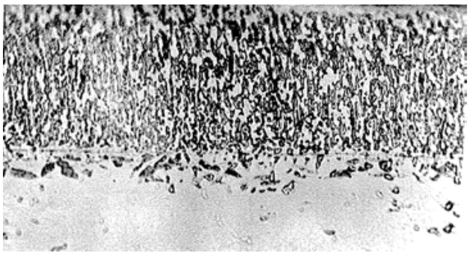
The choice of heat treatment modes is associated with the physicochemical characteristics of the alloy (phase dissolution temperature), operating conditions (resource and level of operating temperatures and stresses), as well as the parameters of thermal technological action in the manufacture of blades (for example, coating application).

In this regard, the temperature and duration of diffusion annealing for the formation of a protective coating were determined taking into account the maximum preservation of the mechanical and physicochemical properties of protected alloy.

The structure of condensed coatings of the Co-Cr-Al-Y type, used to protect the outer surface of the working blades, has been sufficiently studied in the equilibrium state (annealing at 1040…1130 °C, 2…4 hours in vacuum), is γ- a solid solution based on cobalt, containing up to 25 % Cr and 3 % Al, in which there are particles of the intermetallic β – CoAl (up to 30 % by volume) and α – Cr (Figure 1). The Ϭ- CoCr phase, which is in the coatings immediately after deposition, dissolves in the solid solution as a result of annealing. Since chromium reduces the solubility of aluminum in cobalt, excess aluminum is consumed to form β- CoAl.

To analyze the phase composition of coatings deposited on heat-resistant nickel alloys, isothermal sections of the Ni-Cr-Al phase diagrams are used. The intermetallic compound γ′-Ni_3Al has an fcc lattice, the β-NiAl and β-CoAl phases have a bcc lattice.

In β-NiAl, the solubility of chromium at 20 °C is 2.5%, and at 1445 °C it is about 10 %. With a decrease in the aluminum content in the intermetallic compound NiAl, the solubility of chromium in it increases.



a × 400

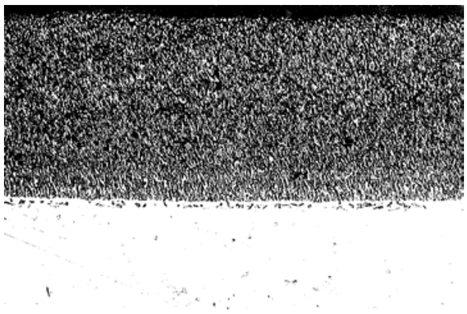


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Figure 1. Structure of Co-Cr-Al-Y on the outer surface of the blades: *a* – IN-738; *b* – ЧС-70

By limiting the formation of the γ′- phase, chromium in Ni-Cr-Al- Y coatings contributes to the preservation of the β – NiAl phase for a longer time, when aluminum is

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consumed for the formation of $\alpha - Al_2O_3$ scale or diffuses from the coating into the protected alloy.

According to the phase equilibrium diagram in Ni-Cr-Al condensate systems at 1020 OS, the transition $\gamma + \beta \leftrightarrow \alpha + \gamma'$ should be observed.

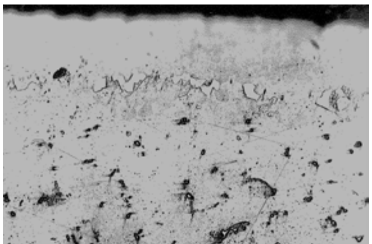
At higher temperatures, $\gamma + \beta$ – phases will prevail in the structure of the coatings, and with a decrease in temperature, closer to the interface with the surface of the cooled blade being protected, the region of existence of the $\alpha + \gamma'$ - phase expands.

For a suspension coating of the Cr-Al-Si-Ti type, it has been established that at a diffusion annealing temperature equal to or higher than the peritectic reaction temperature (≈1130 OS), layers of 120…160 μm and more are formed in 2…4 hours. A clearly expressed heterogeneous structure of the layer is formed on the basis of the compositions Cr-Al-Si and Cr-Al-Si-Ti with a chromium content of 15…20 and titanium of 4.5…6 wt. % at a silicon content of about 8 wt. % (Fig. 2). If the diffusion annealing temperature exceeds the temperature of the peritectic reaction, the chromium and titanium contents exceed their limit solubility in the melt (Cr-Al-Si) and (Cr-Al-Si-Ti), then the coating thickness decreases almost twice (from 140 to 80 μm).

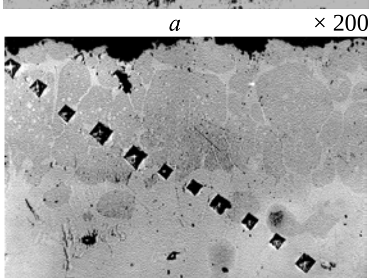
At relatively lower diffusion annealing temperatures, in particular, at 1080 °C, 4 hours, the structure of the Cr-Al-Si-Ti slip coatings is significantly different (Fig. 3) from similar ones with a heterogeneous structure (Fig. 2) and completely coincides with those well known from the literature.

This is due to the long-term existence of the liquid phase in the liquid solution due to the replacement of the Ni_3Al compound with a melting point of 854 °C by the NiAl compound doped with tungsten and molybdenum.

The determining factor in the formation of the coating is the chemical and phase composition of the base, which determines the quantitative transition of nickel and alloying elements in the coating.

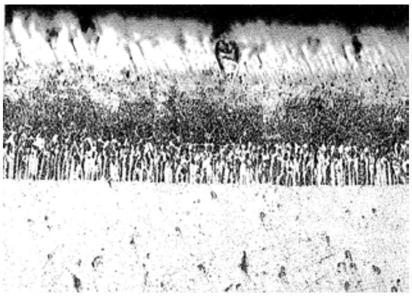


а × 200

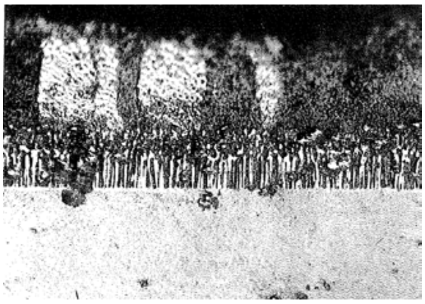


б × 400

Figure 2. Structure of the Cr-Al-Si-Ti slip coating:
а – ЗМІ-3У, 1130 °C, 2 h; *б* – ЭП-539. 1130 °C, 2 h



а × 400



б × 300

Figure 3. Structure of the Cr-Al-Si-Ti slip coating:
а – IN-738, 1080 °C, 4 h.; *б* – ЗМІ-3У, 1050 °C, 4 h

The studied compositions of protective coatings have an effect on the mechanical properties of heat-resistant alloys, which is due, first of all, to the mechanical characteristics of the compounds forming the coating, the mechanical characteristics of the protected alloy, the ratio between the thickness of the coating and the cross-sectional size of the sample, the interaction between the coating and the protected alloy during high-temperature tests. The influence of the temperature cycle of coating application on the mechanical properties of the protected alloy is excluded due to the combination of the thermal cycle of coating formation and the adopted heat treatment of the alloy, as well as its combination with reductive heat treatment during reuse.

With double-sided protection using electron beam coatings СДП-11А and СДП-8 and suspension Cr-Al-Si-Ti (thickness 60…80 and 80…120 μm, respectively), a decrease in the mechanical properties of the metal is not observed in comparison with unprotected samples.

The influence of the studied coatings on the long-term strength of the alloys ЗМІ-3 and ЗМІ-3У is primarily associated with the peculiarities of their destruction in a corrosive environment at high temperatures. Corrosion during the tests contributes to the formation of surface cracks and the development of destruction. The application of protective coatings protects the surface from corrosion destruction and has a positive effect on their long-term strength.

Figures 4 and 5 show that the use of protective coatings provides ЗМІ-3У alloy with a level of long-term strength at 800 and 850°C not lower than that of the alloy without a coating. At the same time, cracking of the protective layer and its separation from the substrate does not occur, and no centers of local corrosion are observed.

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The intensity of the corrosive environment on materials under long-term strength testing conditions depends on the applied heat treatment. Samples that have undergone 850°C aging for 24 hours have a level of long-term strength higher than samples without aging.

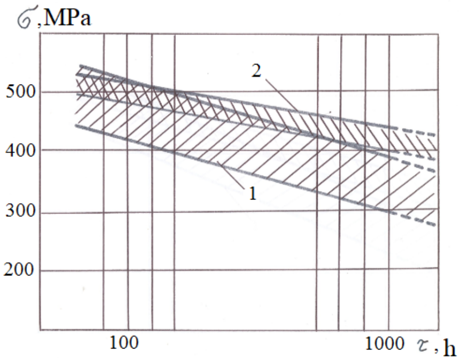

Figure 4. Long-term strength of ЗМІ-3 alloy at 800 °C:
1 – alloy without coating;
2 – alloy with using complex technology

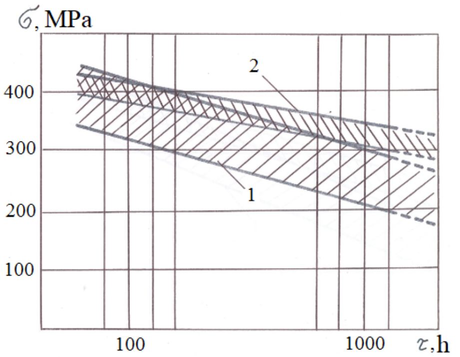

Figure 5. Long-term strength of alloy ЗМІ-3 at 850 °C:
1 – alloy without coating;
2 – alloy with using complex technology.

The heat resistance of the coated samples was determined in an oxidizing atmosphere at 800 and 850 °C. During the tests, it was necessary to obtain a heat-resistant oxide on the surface of the coating that performs protective functions, diffusion of coating elements into the protective oxide, diffusion of coating elements into the protected alloy, diffusion of alloy elements into the coating.

Since the outer zone of the suspension coating is made up of a Ni-Al compound, a protective Al_2O_3 oxide is formed on the surface of the coating at the initial moment of the tests.

Increasing the time of heat resistance tests leads to a deterioration of its adhesion to the coating surface, cracking and delamination.

The depletion of the outer zone of the coating with aluminum during the testing process leads to a change in the structure of the protective oxides and an acceleration of oxidation processes.

Changes in the structure during thermal stability tests of the tested protective coating compositions are shown in Fig. 6–9.

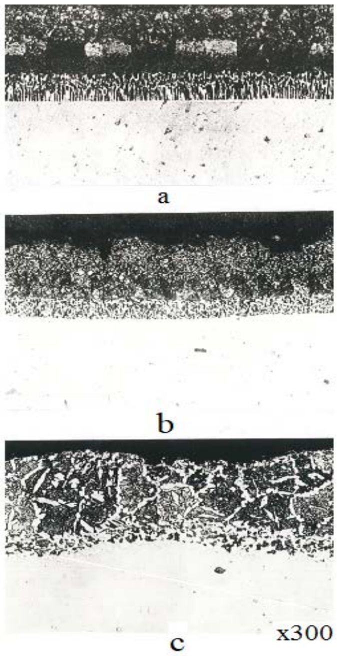

Figure 6. Structure of coatings in the initial state:
a – Cr-Al-Si-Ti; *b* – Cr-Al-Si; *c* – Cr-Fe

As can be seen from the figures, with increasing test time, there is a redistribution of the phase components of the coating, as well as diffusion of coating elements into the substrate and vice versa, from the substrate into the coating. After testing at 860 °C for 600 hours (Fig. 7), the structure of the coatings practically does not change. The outer zones of the suspension Cr-Al-Si-Ti consist of β-NiAl compounds, inside the grains of which there are precipitates of silicides Me_XSi_Y and γ′- Ni_3Al.

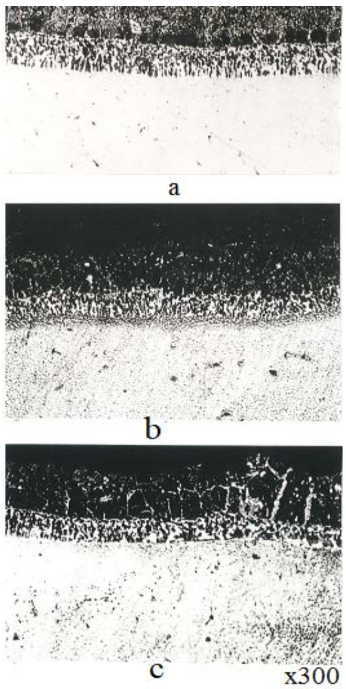

Figure 7. Structure of coatings after testing at 850 °C 600 h:
a – Cr-Al-Si-Ti; *b* – Cr-Al-Si; *c* – Cr-Fe

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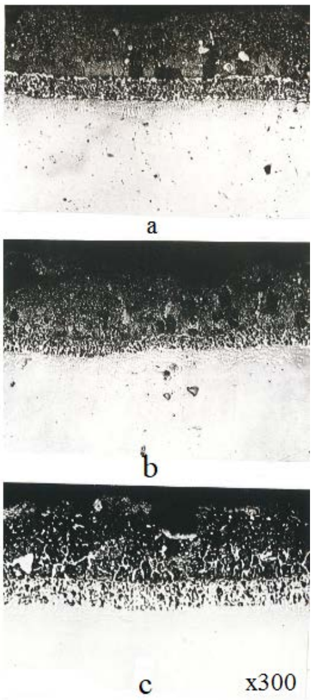

Figure 8. Structure of coatings after testing at 850 °C 1500 h:
a– Cr-Al-Si-Ti; *b* – Cr-Al-Si; *c* – Cr-Fe

The total content of molybdenum and tungsten decreases to 1 %, due to the separation of a dispersed phase based on these elements. In the Cr-Al-Si coating, the inner zone increases, consisting mainly of BCC – solid solutions based on tungsten and molybdenum and carbide phase. In the Cr-Fe coating, the substrate elements diffuse and the intermediate zone PC – base increases. After 1500 hours of testing (Fig. 8), the outer zone of the Cr-Al-Si-Ti suspension PC is dominated by the β – phase (NiAl), enriched in chromium and titanium, carbides of the $Me_{23}C_6$ type and silicides. In the Cr – Al – Si coating, the inner zone "dissolves" into the outer one. In some places, the γ′- phase with an aluminum concentration of up to 10 wt.% is observed. The Cr-Fe coating continues to diffuse into the substrate with the formation of the embrittlement σ- phase [$(Cr, Mo)_X(Ni,Co)$ Y]. After 5000 hours of testing (Fig. 9) the structure of the Cr-Al-Si-Ti suspension can be considered as consisting of two structural zones. The outer zone consists of β- and γ′- phases, the inner zone consists of "islands" of β-phase, μ – phase based on molybdenum, carbide phase, mainly $Cr_{21}(MoW)_2C_6$, silicides, and also the primary (β + γ′) – phase.

On the gas-dynamic stand, the alloys ЧС-70 and ЗМІ-3 showed the highest corrosion resistance. Comparative tests of alloys with protective coatings at 800–900 °C give preference to Co-Cr-Al-Y. They are followed by suspension Cr-Al-Si-Ti with a heterogeneous structure, then diffusion Cr-Fe, applied by diffusion vacuum metallization.

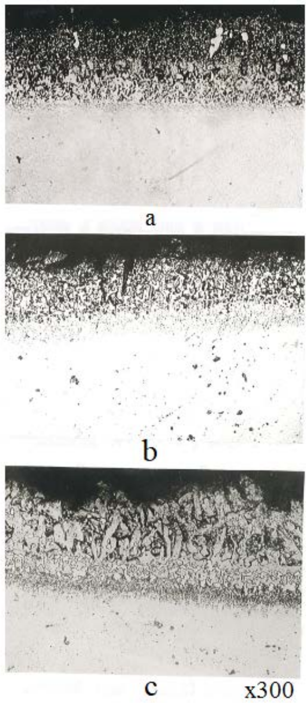

Figure 9. Structure of coatings after testing at 850 °C 5000 h:
a – Cr-Al-Si-Ti; *b* – Cr-Al-Si; *c* – Cr-Fe

The structure of suspension protective coatings Cr-Al-Si-Ti after testing on the gas-dynamic stand of cylindrical hollow samples is shown in Fig. 10. It is identical to the structure of coatings applied to the working blades of the ГТК-10І turbojet turbine, which have been used in real conditions for 9.5 thousand years.

The corrosion kinetics of samples from the ЗМІ-3 alloy with different protective coatings is shown in Fig. 11. The test results determined the following series of resistance: solid samples with Co-Cr-Al-Y, hollow – with double-sided protection, applied in a combined mode, solid with diffusion Cr-Fe, hollow – with external Co-Cr-Al-Y (without internal) and samples without coating.

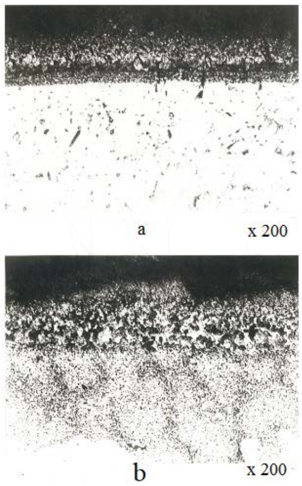

Figure 10. Structure of the coating of the Cr-Al-Si-Ti system:
a – outer surface; *b* – inner surface

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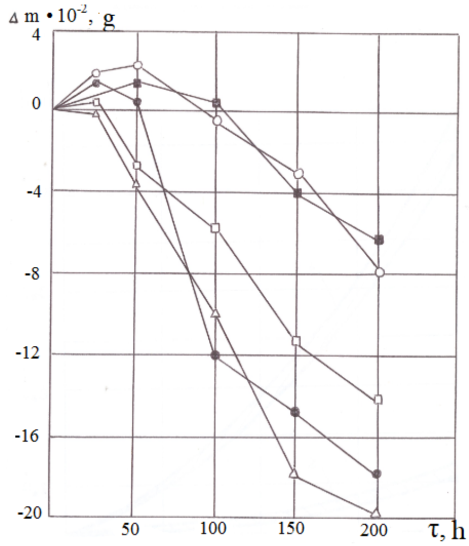

Figure 11. Corrosion kinetics of ЗМІ-3У alloy samples

Figure 12 shows the dependences of the change in the wall thickness of hollow samples depending on the time of testing on a gas-dynamic stand with simultaneous thermal cycling. The nature of the change in the wall thickness of samples without protective coatings is significantly different from similar ones. In the first case, for 200 τ of testing, the wall becomes thinner by 0.780...0.850 mm, in the second – by 122.5...135 μm (practically, by the thickness of the protective coating) in the cross section.

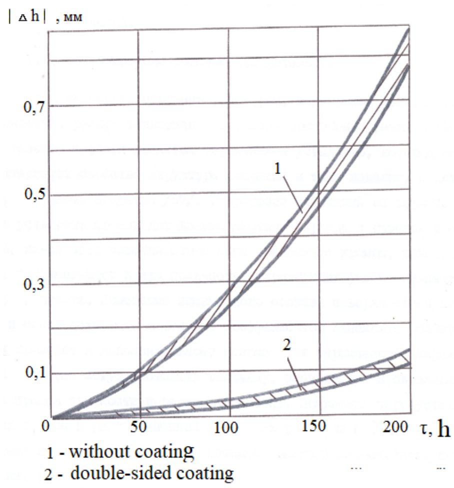

Figure 12. Change in wall thickness of hollow specimens

The conducted studies allow us to conclude that tests of hollow samples with a duration of 50, 100, 150 and 200 hours correspond to the real operation of working blades in a gas turbine for 5000, 10000, 15000 and 20000 hours, respectively, in terms of parameters such as:

- condition of the outer surface;
- depth of corrosion penetration;
- structure; dynamics of corrosion damage, including the geometry of samples before and after the test;
- long-term strength.

All these parameters and research results allow us to predict the durability of gas turbine parts both without protective coatings and with double-sided protection. Thus, without taking into account the corrosion effect at a nominal stress in the average cross-section of 120 MPa, the service life of the working blades is determined at 32 thousand hours (Fig. 13), and taking into account the corrosion effect and changes in wall thickness (according to the test results – a decrease for every 5 thousand hours by 5–7 %) – 25 thousand hours. When using double-sided protection using complex technology, the service life of the blades should be 35 thousand hours.

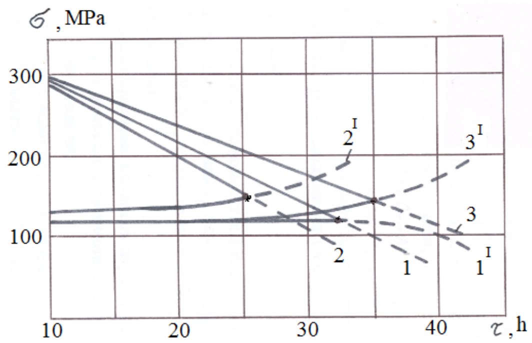

Figure 13. Durability of ГТК-10І workingblades:
1 (1^I) – excluding oxysulfide corrosion;
2 (2^I) – including oxysulfide corrosion;
3 (3^I) – blades protected using comprehensive technology (including oxysulfide corrosion)

Conclusions

1. It is shown that the formation of thermodynamically stable coatings in the complex multicomponent system Cr-Al-Si-Ti is most effectively carried out at a temperature equal to or higher than the peritectic reaction temperature (≈ 1130 °C).
2. It is shown that at relatively lower coating formation temperatures (1080°C, 4 hours), the structure of the slip coating is significantly different from similar ones with a heterogeneous structure and fully corresponds to the classical RT-22A type.
3. It is established that the strength characteristics of heat-resistant superalloys when using complex protection technology at temperatures of 800 and 850 °C do not decrease.
4. The increase in heat resistance is due to a favorable combination of components and a perfect coating structure.
5. Slip coatings Cr-Al-Si-Ti with a heterogeneous layer structure ("high-temperature") have higher resistance than "low-temperature".
6. The projected service life of the working blades increases by 10 thousand hours when using their double-sided protection using integrated technology.

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ВПЛИВ РЕЖИМІВ ТЕРМІЧНОЇ ОБРОБКИ НА СТРУКТУРУ ЗАХИСНИХ ПОКРИТТІВ

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Мета роботи. *Підвищення довговічності робочих порожнистих лопаток ГТК-10І за рахунок двостороннього захисту їх профільної частини.*

Методи дослідження. *Дослідження мікроструктури проводилися на мікрошліфах під мікроскопом «Неофот-2» і мікроскопом-аналізатором «Стереоскан». Мікротвердість вимірювали приладом ПМТ-5. Випробування на короткочасну міцність (ГОСТ 1497-61, ГОСТ 9651-61, ГОСТ 1497-84) проводили на стандартних циліндричних зразках (діаметр робочої частини 5мм, довжина 25мм) при температурах 200, 800, 900 і 1000 °С на*

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розривній машині марки УМЭ-10ТМ. Випробування на тривалу міцність (ГОСТ 10145-81) проводили на стандартних циліндричних зразках при температурах 800, 900, 1000 °С і відповідних навантаженнях 600, 400, 180 МПа на машині АИМА-5-2 шляхом одновісного розтягування зразків при постійному навантаженні. Порівняльні експериментальні дослідження високотемпературної корозії сплавів проводилися в синтетичній золі за методикою, яка широко застосовується в галузі. Для корозійних випробувань використовувалися стандартні циліндричні зразки (діаметр ∅10 мм, довжина l = 12 мм), на які після попереднього знежирення, вимірювання і зважування на аналітичних вагах з точністю (± 0,0005 г), наносилася на їх поверхню синтетична зола в кількості 12 мг / см^2, що імітує продукти згоряння газотурбінного палива, які розміщувалися і витримувалися в печі на платформі з вогнетривкого матеріалу в повітряній атмосфері.

Отримані результати. *Проведено дослідження впливу двостороннього захисту профільної частини робочих порожнистих лопаток ГТК-10І. Показано, що формування покриття найефективніше здійснюється при температурі рівної або більшої температури перитектичної реакції (≈1130 °С). Встановлено, що міцністні характеристики жароміцних сплавів при використанні комплексної технології захисту при температурах 800 і 850 °С не знижуються. Показано, що при відносно нижчих температурах формування покриття (1080 °С, 4 годин), структура шлікерного покриття значно відрізняється від аналогічних з гетерогенною структурою і повністю відповідає класичній типу RT-22A. Встановлено, що прогнозований термін служби робочих лопаток збільшується на 10 тис. годин при використанні двостороннього їх захисту за комплексною технологією.*

Наукова новизна. *Отримані результати дають змогу оцінити процеси, що проходять під час нанесення покриттів та експлуатації лопаток і встановити залежності між товщиною, кінетикою та типом покриття і швидкістю корозії.*

Практична цінність. *Отримані результати дозволяють рекомендувати розроблені покриття та технології нанесенні, ядля збільшення характеристик міцності та довговічності експлуатації виробів.*

Ключові слова: *жароміцні нікелеві сплави, захисне покриття, структура покриття, високотемпературна корозія, міцність.*

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