КОНСТРУКЦІЙНІ І ФУНКЦІОНАЛЬНІ МАТЕРІАЛИ

STRUCTURAL AND FUNCTIONAL MATERIALS

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INFLUENCE OF THE WORKING ENVIRONMENT ON THE HIGH-TEMPERATURE CORROSION OF GAS TURBINE UNIT PARTS

Purpose *The main objective of the work was to study the influence of the working environment on the performance of the ГТК-10I hollow working blades.*

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. Phase composition and lattice periods of the main components were measured on a ДРОН-1 diffractometer in copper Kα radiation. The content of chemical elements was measured on a REM-106I scanning electron microscope. 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 10000 ℃ on a УМЕ-10ТМ tensile machine. Long-term strength tests (GOST 10145-81) were performed on standard cylindrical samples at temperatures of 800, 900, 10000 ℃ 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 / cm^2 was applied to their surface, simulating the combustion products of gas turbine fuel of the following composition, which were placed and kept in a furnace on a platform made of refractory material in an air atmosphere.*

Obtained results. *Studies of the influence of the working environment on the performance of the ГТК-10I hollow blades. It is shown that the working environment significantly affects the performance of the ГТК-10I hollow blades. It was established that the outer layer of the profile part did not show deep damage due to their removal by a high-speed gas flow. It was established that corrosion damage begins from the beginning of operation and the damaged layer con-*

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tains sulfides of the TiS and Ti2S3 types. It is shown that the short-term strength of the 3MI-3 alloy relative to the initial values (passport data) decreases by approximately 16–20 %. It was established that due to structural changes in the alloy during operation, the time to fracture of the samples under load decreased by approximately 18–22 %. Based on the studies performed, the use of protective coatings is necessary to increase performance.

Scientific novelty. *Obtained results make it possible to evaluate the processes that occur during operation on the surface of products and to establish relationships between alloying elements concentration and the corrosion rate.*

Practical value. *Obtained results allow us to recommend domestic alloys as a substitute for foreign alloys without losing the properties and durability of the products.*

Key words: *nickel-based superalloys, high-temperature corrosion, phase composition, long-term strength.*

Introduction

The structural elements of gas turbine plants (GTP) during operation are usually subject to several types of loads, each of which causes a characteristic type of damage. Thus, the working and guide blades of gas turbine engines and plants are subjected to stresses determined by a complex of static, vibrational and cyclic (in the general case) temperature loads.

For example, the profile part of the working blade of a turbine in a stable operating mode is subjected to static stresses from centrifugal and gas forces, reaching 200 MPa [1–4]. Due to the temperature gradient established in the blade sections, thermal stresses of a static nature arise in the material.

At the same time, the blade material is subject to high-frequency cyclic stresses caused by blade vibration. The level of these stresses is determined by design and operational factors and can be 100 MPa, and the total (equivalent) – 150 MPa [3–5].

Damage caused, respectively, by static, fatigue and thermostatic loads is influenced by the working environment, under the influence of which corrosion processes occur.

The main factors determining the rate of corrosion damage are the corrosive properties of the working environment and the temperature of the gases at the turbine inlet during the operation of the gas turbine engine.

Almost all works devoted to the study of corrosion destruction processes focus on the presence of alkali metal compounds, vanadium, and lead in the fuel [2, 6–8]. The main source of harmful impurities is the fuel used as the working environment. Natural gas, which is used as a fuel for gas turbines, contains sulfur - the main corrosive impurity in the form of hydrogen sulfide and mercaptan compounds in fairly large quantities. For example, the volume content of hydrogen sulfide in natural gas is 1.5 ... 4.5% [9]. If sodium also enters the flow part of the turbine, sodium sulfate is formed, which contributes to the acceleration of blade corrosion.

Purpose

The main purpose of the work was to study the influence of the working environment on the performance of hollow working blades of the ГТК-10І.

Material and research methods

The development of nickel-based foundry heat-resistant alloys is primarily due to the fact that, in comparison with deformed alloys, 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 heat-resistant alloys for GTP blades was largely facilitated by advances in the development of ceramic materials, equipment and machinery that allow castings with cooling channels to be obtained. For stationary gas turbines, heat-resistant corrosion-resistant alloys based on nickel ЕП-539ЛМ, ЧС-70ВІ, as well as alloys ЗМІ-3 and ЗМІ-3У instead of imported alloys -738 have become widely used. They are used for the manufacture of working blades of gas turbines of the ГТК-10І, ГТК-16 thrusters.

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

Table 1 – Chemical composition of the studied casting alloys

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

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 a 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 10000 °C on a УМЕ-10ТМ brand tensile machine. Long-

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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. 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 blade blade is subject to prolonged high-temperature action of the gas flow in a complex stressed state. Calculation of temperature fields and stress in the ГТК-10І blade in the “start”, “stop” and “steady state” modes, based on the calculation of the boundary conditions of heat transfer for the blade metal, showed that the maximum temperature stress occurs on the concave side, back, leading edge and at the corresponding points on the surface of the internal cavities of the blade, as well as at the points of connection of the internal jumper. Therefore, special attention was paid to the sections in these places during the research.

Analysis of the surface destruction of the ГТК-10І blades showed that its magnitude and nature depend, first of all, on the operating time, the state of the working environment, dusty air, and the speed of the gas flow.

The following are corrosion studies of ГТК-10І blades (operating time more than 18 thousand hours) made of ЗМІ-3 alloy without protective coatings. Metallographic studies of the cross-section of the profile part showed that the depth of corrosion damage of the inner surface of the blades prevails over the damage of the outer surface.

Figure 1 shows the average cross-section with diagrams of corrosion damage of the profile part of the blades after industrial operation for more than 15 thousand hours.

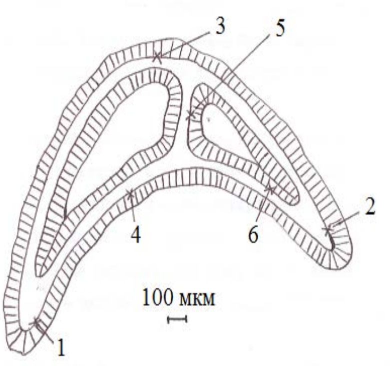

Figure 1. Corrosion damage diagrams:
1–6 – locations for damage investigation

The structure of corrosion damage of the profile part of the blade feather is shown in Figures 2, 3 and 4. It should be noted that the blades are subject to corrosion damage already in the initial period of operation. For example, the depth of the corrosion damage layer after 9.5 thousand hours. operating time has the size of the layer depth after 15 thousand hours. (Figure 5 and 6).

A series of curves were obtained that characterize the concentration distribution of Ni, Cr, Ti, Al, W, Mo, as well as sulfide of the Ti_2S_3 type (Figures 7 and 8).

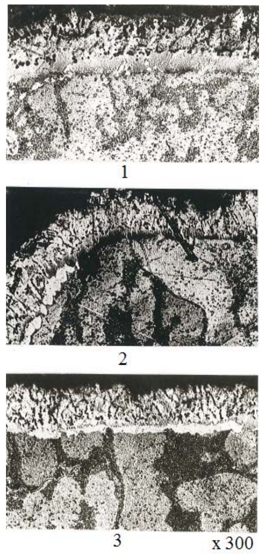

Figure 2. Structure of the profile part of the working blade:
1–3 – points in Figure 1

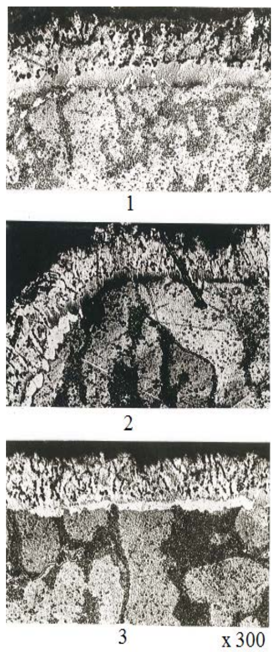

Figure 3. Structure of the profile part of the working blade: 1–3 – points in Figure 1

Analyzing the structure of the corrosion layer and the concentration curves, it is possible, in principle, to

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distinguish three main zones. The most porous outer zone is the NiO oxide, in which alloying elements of the alloy with the content of oxides of the Me_2O_3 type, formed on the basis of Cr_2O_3, are dissolved. The intermediate layer is formed by spinel Ni (Cr, Al) $_2O_4$, includes oxides and alloying elements of the alloy (titanium, cobalt, tungsten, molybdenum, etc.). As inclusions in this layer, apparently, there are small grains (about 3.10 µm), consisting of almost pure nickel. The bottom layer is the thinnest, has an extremely complex composition with sulfide inclusions (for example, TiS and Ti_2S_3 sulfides).

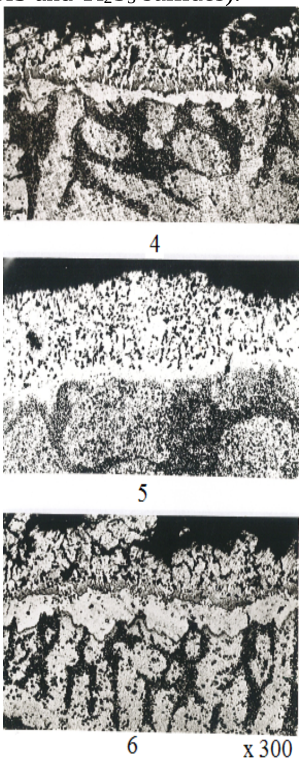

Figure 4. Structure of the profile part of the working blade: 4–6 – points in Figure 1

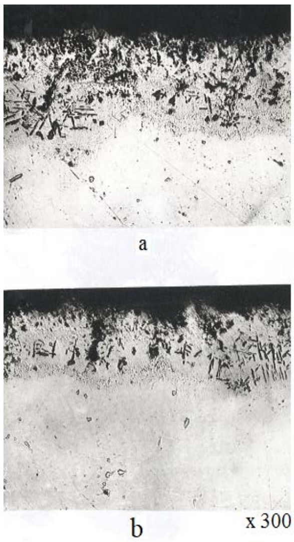

Figure 5. Structure of the surface layer of the working blade after 9.5 thousand hours of operation:
a – inner surface; *b* – outer surface

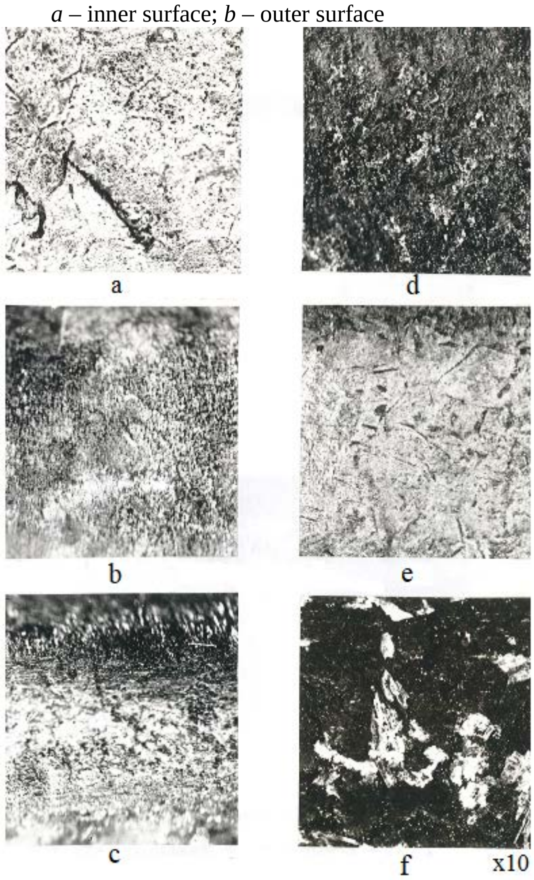

Figure 6 – Surface of samples after testing in molten salts 90 % Na_2SO_4 + 10% NaCl:
a – Х99; *b* – ЧС-70; *c* – ЗМІ-3У; *d* – IN-738; *d* – ВТ 1-0; *e* – ВРН

The results of testing flat cast platinum of heat-resistant alloys and samples of various metals that are the basis or alloying elements for the alloy or protective coating in molten salt 90 % Na_2SO_4 + 10 % NaCl at a temperature of 900 °C for 6 and 24 hours showed that pure chromium (taken as a standard, 100 %) has the greatest resistance to oxysulfide corrosion. Next are promising heat-resistant alloys ЧС-70, or in the original version ЗМІ-2 (85.7%) and ЗМІ-3У (72.4 %), followed by IN – 738 (41.2 %), titanium (26.9 %) and stainless steel 06Х18Н10Т (23.1 %). The lowest resistance was observed in samples of nickel, cobalt, EI-929 (completely dissolved after 24 hours).

The strength properties of the ЗМІ-3 alloy were studied on samples that were cut from working hollow blades after operation.

Short-term mechanical properties of blade parts at different temperatures from the experimental alloy are shown in Figure 9.

The data presented indicate a decrease in the short-term strength of the ЗМІ-3 alloy relative to the initial values (passport data) by approximately 16–20 %. The decrease in the strength and yield strength of the alloy is also characteristic of samples cut from the working blades after operation.

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Samples cut from the working hollow blades after operation were studied for long-term strength and the results obtained were compared with the passport data of the alloy. According to the test results, it was found that due to structural changes in the alloy during operation, the time to failure of the samples under load decreased by approximately 18–22 %. The test data are shown in Figure 10.

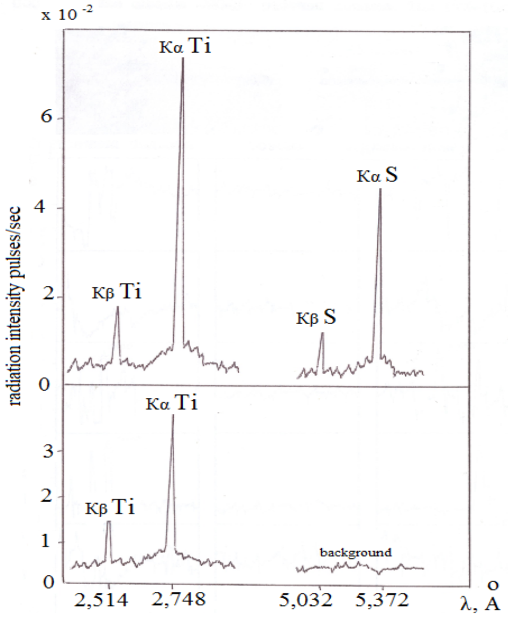

Figure 7. Concentration curves of titanium and sulfur content: *a* – surface layer; *b* – alloy base

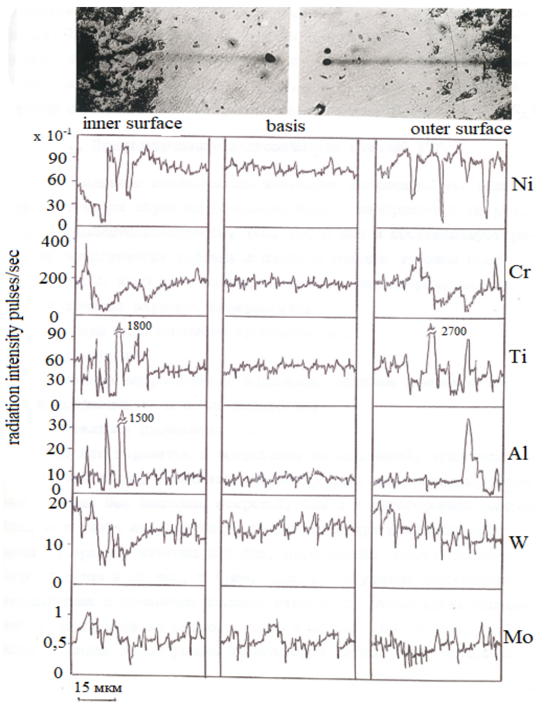

Figure 8. Concentration curves of element distribution in the surface layer of the working blade (alloy 3MI-3)

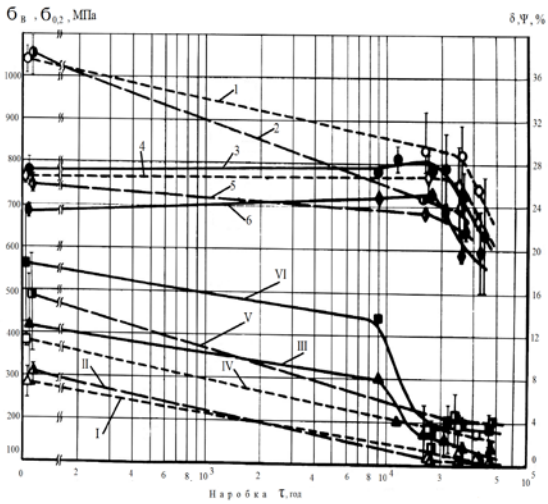

Figure 9. Short-term properties

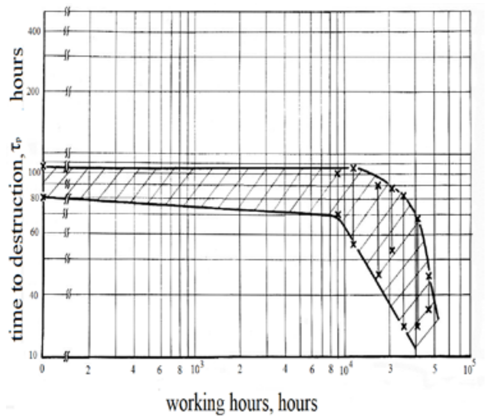

Figure 10. Sustained mitsnist (T = 850 °C, σ = 400 MPa)

Conclusions

1. An investigation was carried out into the flow of the working middle to determine the effectiveness of the working empty blades ГТК-10І. It is shown that the working center essentially contributes to the performance of working empty blades ГТК-10І.

2. It has been established that the outer ball of the profile part has not shown any serious damage due to the impact of the liquid gas flow. It has been established that corrosion damage begins with the beginning of operation and sulfides of the TiS and Ti_2S_3 type are present in the damaged ball.

3. It has been shown that the short-term lifespan of the 3MI-3 alloy at the end of the day (datasheet data) changes by approximately 16–20 %. It was found that as a result of structural changes in the alloy during operation, the hour before the collapse of the cracks under pressure decreased by approximately 18–22 %. To improve efficiency, it is necessary to remove dry coatings.

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ВПЛИВ РОБОЧОГО СЕРЕДОВИЩА НА ВИСОКОТЕМПЕРАТУРНУ КОРОЗІЙНУ СТІЙКІСТЬ ДЕТАЛЕЙ ГАЗОТУРБІННОЇ УСТАНОВКИ

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Мета роботи. *Дослідження впливу робочого середовища на працездатність робочих порожнистих лопаток ГТК-10І.*

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Методи дослідження. *Дослідження мікроструктури проводилися на мікрошліфах під мікроскопом «Неофот-2» і мікроскопом-аналізатором «Стереоскан». Мікротвердість вимірювали приладом ПМТ-5. Фазовий склад і періоди грат основних складових – на дифрактометрі ДРОН-1 в мідному Kα -випромінюванні. Вміст хімічних елементів – на растровому електронному мікроскопі РЕМ-106І. 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 ℃ на розривній машині марки УМЭ-10ТМ. Випробування на тривалу міцність (ГОСТ 10145-81) проводили на стандартних циліндричних зразках при температурах 800, 900, 1000℃ 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.*

Отриманні результати. *Проведено дослідження впливу робочого середовища на працездатність робочих порожнистих лопаток ГТК-10І. Показано, що робоче середовище суттєво впливає на працездатність робочих порожнистих лопаток ГТК-10І. Встановлено, що зовнішній шар профільної частини не показав глибоких пошкоджень за рахунок їх винесення швидкісним газовим потоком. Встановлено, що корозійні пошкодження починаються з початку експлуатації та в пошкодженому шару містяться сульфіди типу TiS та Ti_2S_3. Показано, що короткочасна міцність сплаву ЗМІ-3 відносно початкових значень (паспортні дані) зменшується приблизно на 16–20 %. Встановлено, що внаслідок структурних змін у сплаві при експлуатації, час до руйнування зразків під навантаженням знизився приблизно 18–22 %. Для підвищення працездатності необхідно використання захисних покриттів.*

Наукова новизна. *Отримані результати дають змогу оцінити процеси, що проходять під час експлуатації на поверхні виробів та встановити залежності між легуючими елементами та швидкістю корозії.*

Практична цінність. Отримані результати дозволяють рекомендувати вітчизняні сплави, як замінника закордонного сплаву без втрати властивостей та довговічності експлуатації виробів.

Ключові слова: *жароміцні нікелеві сплави, високотемпературна корозія, фазовий склад, довготривала міцність.*

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