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Hardening protective coatings on niobium alloys, their thermal-cyclic creep and long-term strength

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Abstract

A solution to the problem of protecting niobium from high-temperature, highly intensive oxidation is considered. The isothermal and thermocyclic creep and long-term strength characteristics of a niobium alloy with three coating variants are determined at temperatures of 1400–250°C in air. A test methodology for niobium alloys with coatings under simultaneous loads, high temperatures, abrupt thermal cycles, and an oxidizing environment with radiant heating and non-contact cooling by focusing radiant energy is presented, ensuring reliable determination of mechanical properties. A comparison of ultimate strains, creep rates, and durability under isothermal and thermocyclic conditions for the three coating variants is conducted, demonstrating the advantage of a combined plasma-diffusion coating over silicide and borosilicide coatings. Differences in creep and long-term strength characteristics of the three coating variants are demonstrated, which are explained by the nature of crack development in the coating. The transition from single "sharp" cracks in the coating to regular cracks in the diffusion sublayer with rounded tops ensures an increase in the strength and durability of the niobium alloy.

Keywords: strengthening protective coatings, niobium alloys, thermocyclic creep, plasma diffusion coatings, long-term strength, durability.

Introduction

High heat resistance and moderate density, approximately equal to that of alloy steels, allow niobium alloys to be considered as a replacement for nickel superalloys in gas turbine construction. Niobium alloys also hold promise in power plants. However, the main obstacle to the introduction of niobium alloys remains the problem of their interaction with active gases and high-purity coolants. For example, the oxidation rate of niobium in air at 1100ºC is 300–350 g/h m^2 [1]. Attempts to address the problem of niobium protection are being made by using special heat-resistant alloys with higher resistance to corrosion. Alloying niobium with various additives reduces its oxidation rate in air at 1100ºC to 40–1250 g/h m^2 (however, this level of oxidation intensity is well above permissible limits) [1]. Therefore, the main direction for ensuring high resistance to corrosion destruction of niobium alloys is the use of protective coatings.

Literature review

The development of coatings on niobium alloys has been the subject of considerable research [1-6]. Almost all surface hardening technologies have been tried to strengthen niobium alloys. Traditional galvanic technology was used to apply a Ni coating [1, 6]. However, the solubility of hydrogen in niobium, which dramatically reduces its ductility, hinders the use of galvanic coatings. The aim of the work was to develop a new combined method of surface engineering for the formation of hardening protective coatings on the basis of combination of EAS followed by treatment with PIN.

The most widely used methods of chemical-thermal treatment of niobium alloys are: traditional calorizing, siliconizing, and boriding [7]. Diffusion silicide coatings on niobium alloys exhibit high heat resistance. However, the service life of such coatings and the maximum operating temperatures, especially during thermal cycling, are insufficient. In order to increase the heat resistance and improve the thermal fatigue characteristics of niobium, diffusion coatings based on the Ti-Si system have been developed It has been established that the activities of Ti and Si in the saturating mixture are the main controlling factors for the creation of coatings with high heat resistance. Coatings of optimal composition on niobium have made it possible to increase the temperature limit of its heat resistance to 2000ºC [1, 2, 6].

In the practice of modifying silicide coatings on niobium, numerous combinations have been studied. Two-layer coatings had different phase compositions: the inner layer was $NbSi_2$, while the outer layer consisted of ternary compounds Nb-Al-Si [3, 8]. In order to improve heat resistance, the possibility of increasing the Cr and Ti content in the silicide coating on Nb alloys by sequentially applying diffusion sublayers by immersion in molten salt was studied. The effect of copper on the borosilicate of niobium, as well as the effect of copper and sulfur, was studied. A positive effect was ensured by the combined diffusion saturation of niobium with titanium and zirconium. The thermal fatigue characteristics of niobium are improved by siliconizing in a $TiSi_2$ mixture [7].

The best results to date in protecting niobium alloys are worth noting – the developed method of vacuum activated diffusion saturation. This method enables the deposition of a coating on niobium when Mo, Ti, Cr, Ni, Al, Si, and B are present in the reaction zone. In industrial practice, coating of niobium alloys in liquid metal melts has found application . Low-melting metals with alloying elements are used as transport melts. The feasibility of using an Al-based transport melt with alloying additives of Si, Cr, Mo, Ti, Y, Ni, Zn, and Sn has been confirmed [2, 5].

Gas nitriding is used among the methods of chemical-thermal treatment for surface hardening of niobium alloys. The effect of alloying elements on the nitridability of niobium has been studied. It has been established that a nitride of the NbN type forms on the surface of nitrided Nb alloys. A series of studies on the effect of nitrogen-containing environments on niobium should be noted. A coating was applied to niobium from the gas and solid phases. Ammonia served as the gas phase, and powders containing Si and Al served as the solid phase. This treatment made it possible to obtain complex multilayer coatings. The effect of preliminary plastic deformation on the nitriding kinetics of niobium alloys was studied. The degree of compression was 25...90% [9, 10].

A trend toward transitioning from gas nitriding to glow discharge ion nitriding is also observed in the strengthening of niobium alloys. Ion nitriding temperature is 1000°C, duration is up to 5 hours, and gas pressure is 4–13 mmHg [10]. Thermocyclic ion nitriding technology offers new opportunities for strengthening niobium alloys. This technology is characterized by the fact that the thermal cycling mode creates thermal stresses in the surface layer, which accelerate diffusion. Cyclic glow discharge heating provides the required temperature only in the surface layer of the component without heating the core. The effect of anomalous mass transfer under the influence of thermal stresses accelerates nitrogen diffusion by a factor of 3. Thermal cycling, with heating only the surface layer, reduces energy consumption by up to 10 times compared to the classic isothermal mode [9].

Glow discharge processing is also used for siliconizing niobium. Coatings on niobium obtained by diffusion siliconizing of sintered Mo-(0.5...1.5) Pd layers exhibit heat and thermal stability up to 1900°C [11]. Traditional enameling and slip-diffusion coatings are used to protect niobium alloys. In the literature, this technology is referred to as the fusion deposition method [1, 5]. Powders of the Si-20Cr-5Ti and Si-20Cr-20Fe systems are used in a varnish base with vacuum firing at 1370°C. The powders were applied using electrophoresis. The high performance of slip coatings is noted. The $MoSi_2$-based coating operates at 1400°C in air for 300 hours, while the Si-Cr-Fe coating operated at 1550°C for 4 hours and withstood 553 thermal cycles.

Thermal plasma spraying is used to protect niobium alloys [1, 12]. Spark plasma sintering is also an option for protecting niobium. Work on protecting niobium alloys by vapor-phase deposition (PVD) has been reported. Complex silicide coatings of the $NbSi_2$-$MoSi_2$ type were deposited using vacuum plasma deposition. The presence of a droplet phase, which leads to coating defects, limits the use of PVD methods for protecting niobium. The potential of laser technology for coating niobium has been investigated. Laser technology has been used to deposit metallic sublayers for silicide coatings. The niobium surface is alloyed with tungsten using laser pulses [1].

A number of shortcomings hinder the widespread use of protective coatings. To overcome these, a trend has emerged toward the development of multi-stage technologies. This trend has also emerged in the hardening of niobium alloys. The primary objective is to protect niobium from high-temperature, highly intensive oxidation. Therefore, the effectiveness of heat-resistant coatings on niobium is also determined by their durability at normal temperatures, eliminating oxygen saturation [1, 3, 11]. The thermal stability of niobium coatings was assessed by changing the coating structure and composition [4]. Considerable attention has been devoted to determining the elastic constants of niobium coatings. The high damping properties of niobium coatings, which are provided by the porous structure of the coating, are noted [8, 12, 13].

A significant drawback of protective coatings is the reduced strength and ductility of the base material [1]. This drawback is also inherent in coated niobium alloys. Despite a large number of studies, there is no clarity on this issue. Difficulties in explaining these discrepancies are caused by differences in coating application and testing methods. The wide range of base and coating material combinations and the variety of application technologies prevent comparison of a range of results and the drawing of general conclusions. In the practice of protective coatings, one must accept the phenomenon of a decrease in the initial strength and ductility, at least for the sake of maintaining heat resistance in an oxidizing environment.

For niobium alloys, a coating-induced reduction in mechanical properties was observed both at room temperature and at 1100°C. The coating reduced the strength characteristics of the Nb alloy by 10–40% across virtually the entire temperature range studied. Furthermore, the plastic properties of the composite were 1.5–4 times lower than those of the base [14-16]. In tensile tests of the Nb alloy, embrittlement with a simultaneous reduction in tensile

strength was observed in the temperature range of 500–700°C, which is associated with surface gas saturation. Silicide coatings protect the Nb alloy from brittle fracture, although they reduce the original mechanical properties [4, 5, and 7. 11. 12].

A number of positive effects have been noted during nitriding of niobium alloys. The elastic modulus E of a nitrided niobium alloy increases with both temperature and nitriding time. The elastic limit increases by 3-5 times with increasing nitriding time. With increasing nitriding temperature, the ultimate tensile strength monotonically increases by 1.5-2.0 times, while the relative elongation monotonically decreases when tested at room temperature. Increasing the nitriding temperature from 1100 to 1500°C with a 1-hour hold increases the hardness of niobium alloys from 1400 to 2000 kg/mm2. The ultimate tensile strength of pure niobium increases by 25-30% at 800°C and has virtually no effect on heat resistance at 1000°C. For the VN-3 alloy, creep and long-term strength tests at 900...1400ºC showed an increase in the time to failure and an improvement in creep resistance characteristics by 1.3...2.5 times, which do not lead to a decrease in ductility [6, 9, 10].

The increased heat resistance of niobium alloys is attributed to the stabilization of processes occurring within and along grain boundaries due to the precipitation of dispersed nitride particles [1]. This increased heat resistance is due to coherent dispersed nitride phases precipitating within the grains and along their boundaries, as well as in the form of individual chains along block boundaries. A significant drawback of nitriding niobium alloys is the increased brittleness of diffusion layers [2]. One cause of the brittleness of nitrided Nb alloys may be treatment with ammonia.

The range of experimental methods for testing coatings on niobium alloys is quite broad – from nano- and microindentation to multiparameter bench testing [17]. It should be noted that the state of experimental methods for determining coating properties is characterized by a wide variety and variability in testing methods, specimen shapes and sizes, testing regimes, and heating and cooling methods. Therefore, it is impossible to compare the results of individual studies. The results of coating property determination are also incomparable due to differences in coating design, the thickness ratios of the various layers, application technologies, and surface preparation methods prior to coating application. A brief review and analysis of the studies demonstrates the relevance of developing protective coatings on niobium alloys. However, the growing number of studies and publications does not provide any clarity in addressing this complex issue.

The aim of the work is to determine the thermocyclic creep and long-term strength of a niobium alloy with a two-layer combined coating at temperatures of 1400 ºC in air, compare these characteristics with two technologies of diffusion silicide coatings and establish differences in the destruction of these coatings during creep.

Research Methodology

A method for accelerated testing of materials with heat-resistant coatings in air under thermal-cyclic creep conditions was used. This method is standardized in Ukraine [2, 18]. The main damaging factor is abrupt cyclic thermal changes. Continuous recording of the creep curve characterizes all changes in the coating and in the adhesive contact zone with the substrate, right up to specimen failure. The trend in the development of high-temperature testing is toward a transition from isothermal to thermocyclic modes. During thermocyclic testing, the oxidation rate in air is significantly higher than during isothermal testing [2, 18]. This circumstance allows for a reduction in test duration and serves as the basis for the development of accelerated coating testing methods. A leading trend in coating testing is the application of thermomechanical fatigue methods (TMF) [2, 18]. This new technique simulates the simultaneous action of operational factors: mechanical load, high temperatures, abrupt thermal changes, and an oxidizing environment. The non-additivity of the softening effect requires testing under the simultaneous action of operational factors. Only in this way can the most reliable information about the properties of coatings be obtained. The technique is implemented in the Nutcracker laboratory setup [2, 18]. A distinctive feature of the setup is heating and cooling the sample by focusing radiant energy in an optimized closed cavity with cold mirror walls. Radiant heating, in contrast to heating methods by directly passing an electric current through the sample and heating with high-frequency currents (HFC), eliminates the effects of electroplastic and magnetoplastic effects. These effects lead to errors of tens of percent when determining strength and ductility. Accelerated cooling of the sample is achieved by focusing its own thermal radiation on an absorber [18]. The advantage of cooling by focusing its own radiation is the absence of direct contact between the sample and the cooling medium, which ensures uniform cooling along the perimeter and height of the sample, and also increases the cooling rate due to the absence of film and nucleate boiling. Contactless cooling completely eliminates the erosive, corrosive and adsorption effects of the cooling medium.

he cool mirror walls of the optical chamber ensure minimal thermal inertia. This enables high heating and cooling rates. A distinctive feature of the setup is the ability to continuously visually monitor the specimen's condition during testing. Illuminated by radiant energy, the specimen is conveniently viewed through a hole in the mirror wall of the optical device. Photographing the specimen during testing provides data on its deformation, the occurrence of defects and cracks on the surface, their sizes, and the distances between them. Photography records the moments of crack initiation in the coating and its delamination. Taken together, such photography provides an understanding of the specimen's deformation kinetics up to its failure. A prerequisite for the normal operation of parts made of niobium alloys is to ensure a minimum level of plastic deformation, as well as a minimum rate of its accumulation. Therefore, the characteristics of isothermal and thermocyclic creep during tension of sheet niobium alloy specimens with a thickness of 1-2 mm were adopted as criteria. A creep curve or short-term tensile stress diagram was constructed as a result of the tests. A thermocyclic creep curve was constructed as an envelope of the maximum strain peaks per cycle. The creep curves were used to determine the relative strain at failure (ε_p) and the time to specimen failure (τ_p), as well as the minimum creep rate. The creep curve was also used to determine the strain when defects appeared in the coating. The temperature on the specimen was measured and controlled using a platinum-rhodium thermocouple (TPR-0.6). The temperature gradient along the length of the working section did not exceed 1%. The setup was equipped with a computer system for monitoring and recording the parameters [18]. Three coating variants were tested:

I – silicide composition Si-Fe-Cr-Ti, using the slip method;

II – borosilicide composition Si-B-Ti, using the slip method;

III – a complex coating with a plasma-spun molybdenum disilicide ($MoSi_2$) sublayer with an outer surface layer obtained by diffusion saturation with elements, the main ones being silicon and boron.

Diffusion saturation of all three variants was carried out in a vacuum. To study the effect of stress level during creep, tests were conducted in the stress range of 40–70 MPa. This made it possible to plot long-term tensile strength curves, the dependence of the minimum creep rate on stress, as well as creep limits and long-term tensile strength. The
test temperature conditions are listed in Table 1.

Table 1

Characteristics of temperature test conditions

Mode No	Type of regime	T_{max},°C	T_{min},°C	Heating time, s	Cooling time, s
1	Isothermal	1400	–	–	–
2	Thermocycling	1400	650	14	14
3	Thermocycling	1400	250	60	60
4	Thermocycling	1400	250	20	60

At least 3-5 specimens were tested under each loading regime. Mathematical processing of the experimental data was performed using standard mathematical statistics methods.

Research Results. Creep Characteristics Study

In analyzing the isothermal and thermocyclic creep results, primary attention was paid to the plasma-diffusion coating (III). Results for the slip-fired diffusion coatings (I and II) will be presented in the comparative analysis of coating damage. Plasma-diffusion coating was used to form a multilayer coating on the surface of a niobium alloy. The plasma-sprayed molybdenum silicide layer exhibits significant thickness variation (h = 100...350 µm, $H_{\mu}^{20} = 6880$ MPa). The functional dependence of adhesion strength, residual stresses, and critical deformation of the substrate on the coating thickness was demonstrated in [2, 18]. Variation in the thickness of silicide coatings on niobium alloys was noted [2, 6]. The dependence of durability on coating thickness on a niobium alloy is extreme. Therefore, more attention should be paid to coating thickness and its optimization, with separate studies being conducted. Figure 1 shows the average creep curves for isothermal (1) and thermocyclic (3) testing modes.

It is noteworthy that the formation of visible cracks on the coating surface (marked with crosses in Fig. 2) occurs long before complete failure of the specimens. More than 70% of the composite's service life is accounted for by the service life with cracks in the coating. Moreover, the appearance of cracks on the coating surface has virtually no effect on the specimen's creep behavior (after cracking, the steady-state creep rate remains unchanged). An important feature of this composite is the higher service life of specimens tested under thermal cycling conditions (3) than under isothermal conditions (1) at stresses above 45 MPa. This is also indicated by the relative positions of the long-term tensile strength (Fig. 2) and creep rate (Fig. 3) curves for specimens with plasma-diffusion coating.

As Figures 1–3 show, with test durations of less than 600–800 minutes (the number of thermal cycles before failure does not exceed 400), the weakening effect of thermal fatigue phenomena does not have time to fully manifest itself. At the same time, the average temperature during isothermal creep is higher than during thermal cycling, which explains the lower durability of the composite in this case. With a larger test duration (loads less than 40 MPa), thermal fatigue phenomena begin to dominate the overall damage accumulation in the composite, and the durability during thermal cycling creep becomes lower than that during isothermal creep.

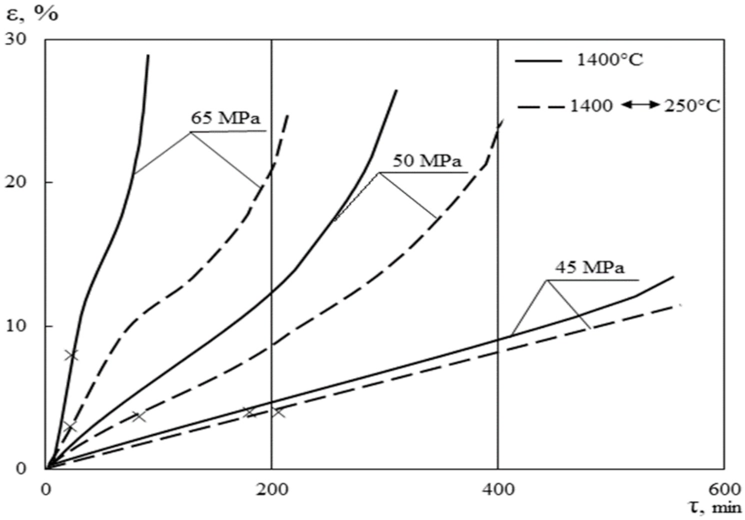

Fig.`1. Averaged creep curves of a niobium alloy with a plasma-diffusion coating for various test conditions

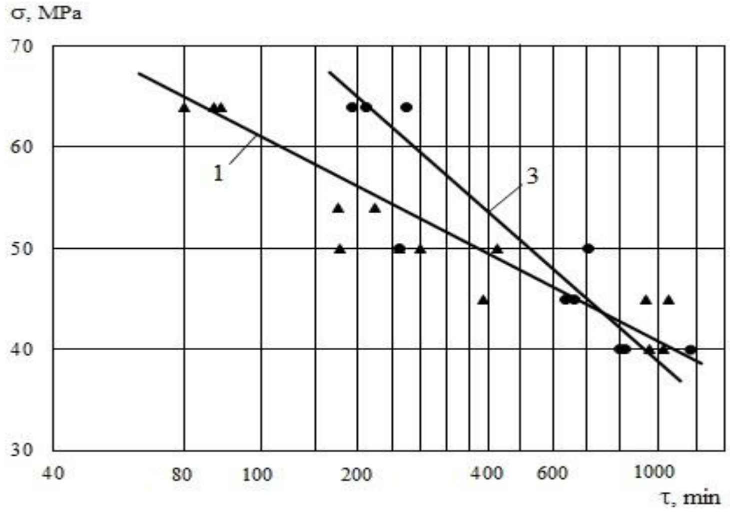

Fig. 2. Durability curves of a niobium alloy with a plasma-diffusion coating for isothermal (1) and thermocyclic (3) loading modes

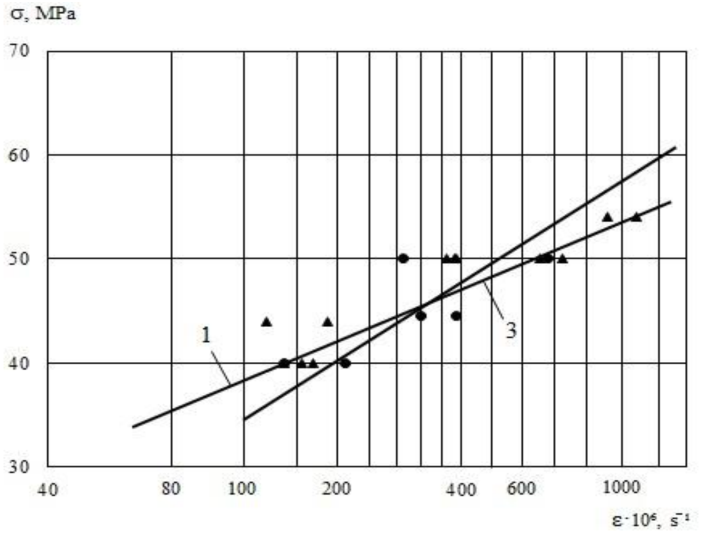

Fig. 3. Minimum creep rate as a function of stress for a niobium alloy with a plasma-diffusion coating under isothermal (1) and thermal cycling (3) testing conditions

The nature of damage and failure of the composite. The study of the composite included observation of the specimen surface during testing. Initially, a network of cracks appears on the specimen surface. Subsequently, almost all of the cracks begin to open, indicating a uniform distribution of deformations along the length of the specimen's working section. Droplets of low-melting compounds appear on the coating surface. As the third stage of creep approaches, when crack opening becomes quite large, the incipient boiling of these melts becomes clearly visible at the crack mouths. The distributed compounds fill almost all cracks completely, preventing the penetration of the aggressive gas environment deep into the coating. Furthermore, this melt possesses healing properties, inhibiting crack opening. In this case, at elevated temperatures, the multifunctional capabilities of the plastic melt are evident – inhibiting both corrosive and mechanical failure. Analysis of the deformation kinetics of the composite during a single heating cycle allowed us to conclude that this phenomenon is most pronounced during thermal-cyclic creep.

It was observed that the compounds filling the cracks melt at temperatures above 1300 ºC. At lower temperatures during thermal cycling, these compounds crystallize, resisting crack opening. Minor changes in the failure mode of the plasma-diffusion coating (III) were detected when comparing the creep of the specimens under different loading conditions. The first visible cracks on the coating surface under the thermal cycling test mode (3) appear at relative creep strain levels of 4...5%, while under the isothermal mode (1) – at 5...7%. This difference is apparently explained by a change in the coating plasticity depending on temperature (under the thermal cycling mode, the average temperature is lower than under the isothermal mode). At the same time, no change in the density of cracks appearing in the coating was detected. Figures 4 and 5 present the probability curves of the crack pitch arising in the coating on the specimen surface after isothermal and thermal cycling tests, respectively. As can be seen from the figures, this parameter, at a 50% probability level, ranges from 0.75 to 0.95 mm. The slight slope of the probability curves indicates a small spread in crack pitch values along the length of the specimens.

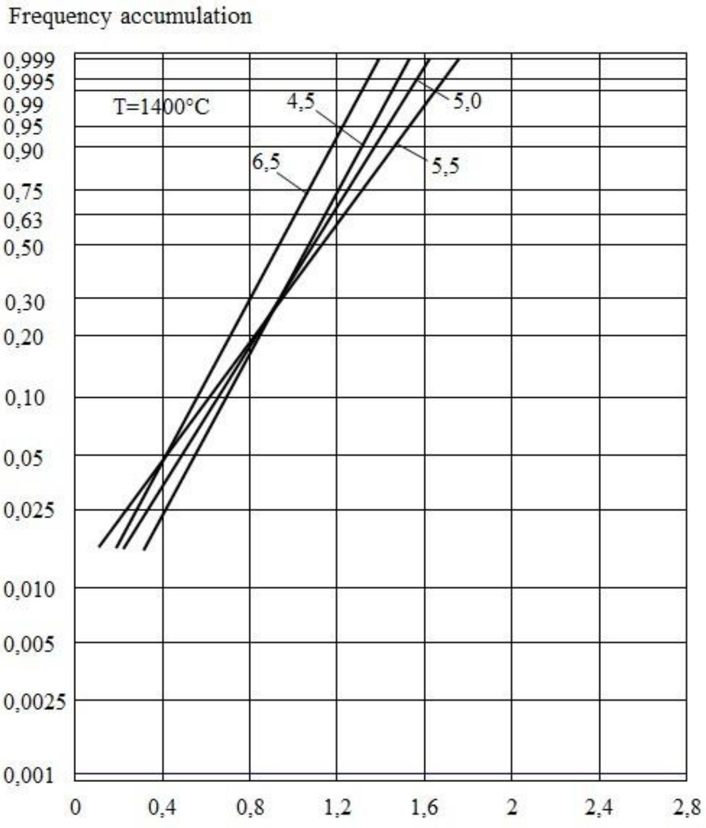

Fig. 4. Probability curves of crack pitch distribution in a plasma-diffusion coating (III) formed during isothermal creep

Post-test microstructural studies of plasma-diffusion-coated specimens revealed that cracks in the coating initiate during creep, primarily at the interface between the plasma and diffusion layers of the coating.

These cracks originate from individual discontinuities in the diffusion layer in the as-received condition. Crack propagation occurs within the diffusion layer of the coating. Crack growth is inhibited by the rounded nature of the pores and the increased plasticity of this layer. Crack growth deeper into the specimen is typically inhibited by the sublayer.

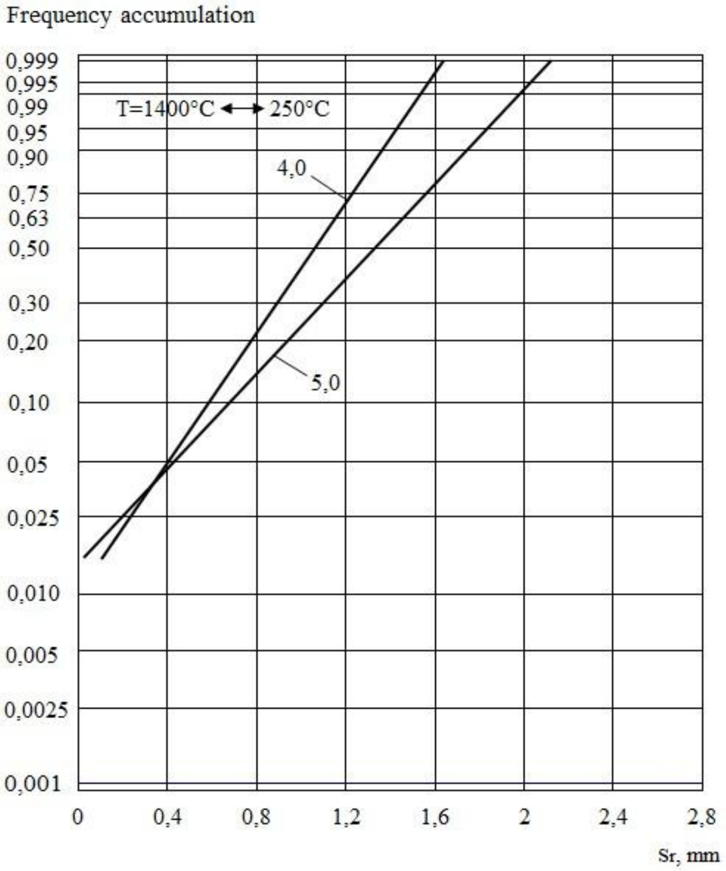

Fig. 5. Probability curves of the distribution of the crack pitch in the plasma-diffusion coating (III), formed during thermocyclic creep at different loading levels

It has been observed that atmospheric oxygen penetrates through cracks that have reached the coating surface, causing preferential oxidation of the diffusion silicide layer. This phenomenon is particularly characteristic of samples with significant durability. This effect almost always manifests itself at low loads and is often absent at stresses above 50 MPa. It can be assumed that this layer inhibits the progression of the oxidation process deeper into the substrate.

Comparison of Creep and Damage of Coatings. To highlight the specific features of the composition with the plasma-diffusion coating (III), the creep characteristics of this composition were compared with those obtained for compositions with other silicide coatings: I - (Si-Fe-Cr-Ti) and II - (Si-B-Ti). The comparison was conducted for isothermal (1) and thermocyclic (3) testing modes at a stress level of 50 MPa. Figures 6, 7, and 8 show the average characteristics of these compositions.

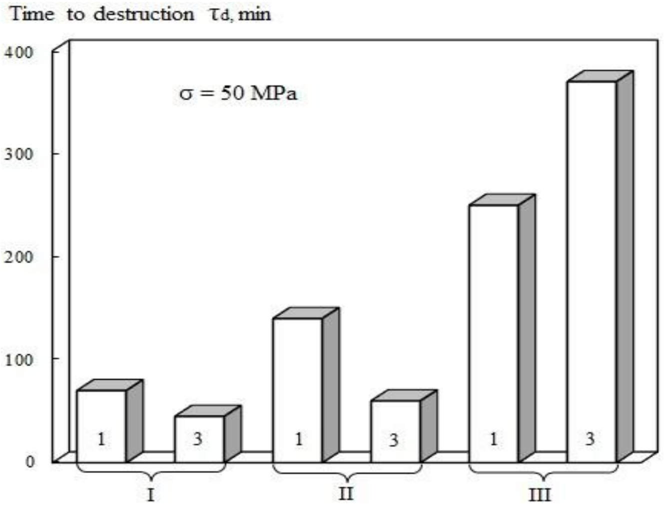

Fig. 6. Comparison of the durability of a niobium alloy with coatings: I – (Si-Fe-Cr-Ti); II – (Si-B-Ti); III – plasma-diffusion mm

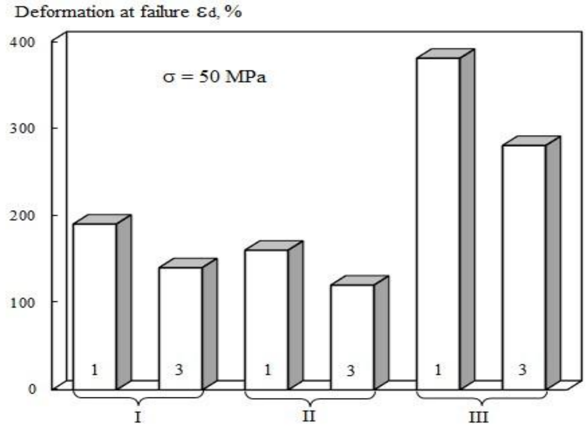

Fig. 7. Comparison of the durability of a niobium alloy with coatings: I – (Si-Fe-Cr-Ti); II – (Si-B-Ti); III – plasma-diffusion

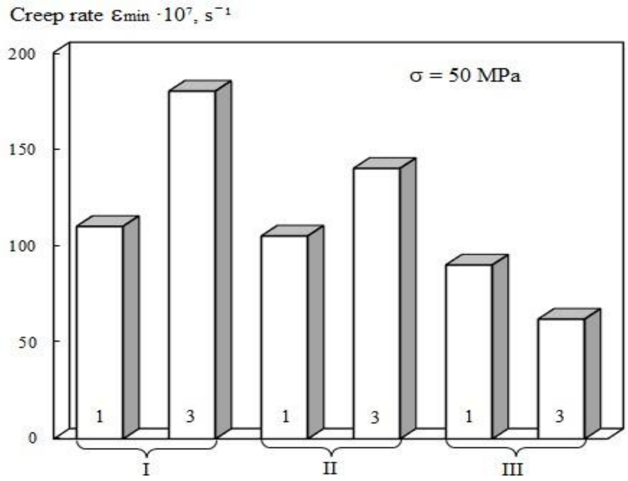

Fig. 8. Comparison of the durability of a niobium alloy with coatings: I – (Si-Fe-Cr-Ti); II – (Si-B-Ti); III – plasma-diffusion

Based on the comparison results, the following conclusions can be drawn: the performance characteristics of the plasma-diffusion coating (III) are significantly higher than those of the compared coatings. Particularly noteworthy is the significant increase in deformation at failure of the samples with the plasma-diffusion coating (III) compared to coatings (I) and (II) – by 1.7...1.75 and 1.9...2.0 times, respectively. Since the temperature processes of diffusion saturation during application of all three coating systems are virtually identical, it can be concluded that the plastic properties of the base material and the compositions under consideration are identical. Consequently, the overall increase in plasticity of the composition is due to the increased plasticity of the plasma-diffusion coating (III) itself compared to the other two coatings. Under a load of 50 MPa, the time to failure of the composite with plasma-diffusion coating (III) under thermal cycling testing is longer than under isothermal testing. This fundamentally distinguishes this composite from the comparable composites, for which thermal cycling testing resulted in a comparatively reduced durability. Cracks in plasma-diffusion coating (III) are uniformly distributed across the test section of the specimen, while the comparable coatings exhibited isolated cracks only in the fracture zone of the specimen. The significant softening effect of cracks in coatings (I) and (II) was also evident in the creep behavior of the compared composites. The appearance of cracks in these coatings resulted in rapid specimen failure (transition from creep to softening). However, cracks on the surface of plasma-diffusion coating (III) did not affect the creep behavior. As a result of the above-mentioned properties, the composition with the plasma-diffusion coating (III) has a durability that is 1.9 and 3.7 times higher under isothermal conditions and 6.8 and 8.5 times higher under thermal cycling conditions, respectively, than the niobium alloy with coatings (II) and (I).

Conclusions

The isothermal and thermocyclic creep behavior and long-term strength of a niobium alloy with three coating variants were investigated in air at temperatures of 1400–250°C. A testing methodology combining simultaneous mechanical loading, high temperatures, rapid thermal cycling, and an oxidizing environment with radiant heating and non-contact cooling enabled reliable determination of mechanical properties. Comparison of ultimate deformation, creep rate, and durability under isothermal and thermal cycling conditions demonstrated the superior performance of the combined plasma–diffusion coating over silicide and borosilicide coatings. Its effectiveness is associated with higher coating ductility, the presence of thin barrier sublayers, a discontinuous structure, low-melting phases promoting defect healing, and improved corrosion and thermal fatigue resistance. As a result, the combined coating increased durability by 1.9–3.7 times under isothermal creep conditions in air (1400°C, 50 MPa) and by 6.8–8.5 times under thermal cycling creep conditions (1400–250°C, 50 MPa). The observed differences in creep resistance and long-term strength are also attributed to the crack propagation mechanism: the transition from isolated sharp coating cracks to regular cracks with rounded tips in the diffusion sublayer contributed to enhanced strength and service life of the niobium alloy.

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Лопата Л.А., Лопата О.В., Качинська І.Р., Рибак І.П., Солових А.Є. , Катеринич С.Є. Зміцнюючі захисні покриття на ніобієвих сплавах, їх термоциклічна повзучість і тривала міцність.

Представлено вирішення задачі захисту ніобію від високотемпературного високоінтенсивного окиснення. Визначено характеристики ізотермічної та термоциклічної повзучості та тривалої міцності ніобієвого сплаву з трьома варіантами покриттів при температурах 1400...250°С на повітрі. Розглянута методика випробувань ніобієвих сплавів з покриттями при одночасному впливі навантажень, високих температур, різких теплозмін та окисного середовища при променистому нагріванні та безконтактному охолодженні фокусуванням променистої енергії забезпечила достовірність визначення механічних характеристик. Проведено порівняння граничних деформацій, швидкості повзучості та довговічності при ізотермічному та термоциклічному режимі трьох варіантів покриттів та показало перевагу комбінованого плазмово-дифузійного покриття перед силіцидним та боросиліцидним покриттями. Показано відмінність у характеристиках повзучості та тривалої міцності трьох варіантів покриттів, що пояснюється характером розвитку тріщин у покритті. Перехід від одиничних «гострих» тріщин у покритті до регулярних тріщин у дифузійному підшарі із заокругленими вершинами забезпечує збільшення міцності та довговічності ніобієвого сплаву.

Ключові слова: зміцнюючи захисні покриття, ніобієві сплави, термоциклічна повзучість, плазмово-дифузійні покриття, тривала міцність, довговічність