UDC 621.438:621.793

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INFLUENCE OF YTTRIUM CONCENTRATION AND DEPOSITION METHOD ON THE CRYSTAL LATTICE PARAMETERS OF KNA-82 SEALING COATINGS

Purpose. *To establish the patterns of changes in the crystal lattice parameters of the KNA-82 sealing coating depending on the yttrium concentration within the range of 0.1–0.5 wt.% and the deposition method -flame spraying and ion-plasma deposition and to determine the alloying range in which structural changes are most controllable.*

Research methods. *The lattice parameters were determined by X-ray diffraction analysis using CuKα radiation (λ = 1.5418 Å). Interplanar spacings were calculated according to the Wulff-Bragg law, while the cubic lattice parameters were determined using the Miller indices of the diffraction peaks. The initial diffraction angles and calculated values were obtained from the experimental data table.*

Results. *For ion-plasma coatings, increasing the Y content from 0.1 to 0.5 wt.% resulted in an increase in both analyzed lattice parameters: from 4.0525 to 4.0543 Å and from 4.2297 to 4.2332 Å. For flame-sprayed coatings, the dependence was non-monotonic: at 0.3 wt.% Y, a local decrease to 4.0519 and 4.2322 Å was observed, followed by an increase to 4.0567 and 4.2356 Å at 0.5 wt.% Y. The most pronounced difference between the deposition methods was observed at 0.3 wt.% Y.*

Scientific novelty. *The regularities of the effect of yttrium concentration within the range of 0.1–0.5 wt.% on the crystal lattice parameters of KNA-82 coatings were established. It was shown that the nature of structural changes depends significantly on the coating deposition method. The obtained results make it possible to substantiate a rational yttrium content with consideration of the deposition technology.*

Practical value. *The obtained results can be used to select a rational yttrium content in KNA-82 coatings depending on the deposition method and the required structural characteristics.*

Key words: *sealing coating, KNA-82, yttrium, crystal lattice parameter, X-ray diffraction analysis, flame spraying, ion-plasma deposition, gas turbine engine.*

Introduction

Reducing radial clearances limits working-gas leakage and contributes to an increase in gas turbine engine efficiency; however, it also increases the probability of contact between the blade tips and casing components due to thermal and centrifugal deformation of the rotor. To maintain minimum radial clearances in the gas path of a gas turbine engine (GTE), sealing coatings are used that provide controlled running-in of the contact surface during interaction with the tips of the rotor blades. The performance of such coatings is determined by their structural and phase state, thermal stability, wear and heat resistance, as well as their ability to retain the required properties during prolonged high-temperature operation.

For the medium- and high-temperature zones of gas turbine engines, nickel-based sealing materials remain promising. Their performance characteristics are largely determined by the composition of the metallic matrix, the presence of solid lubricant components, and the deposition technology. KNA-82 belongs to this class of materials. Its metallic base consists of nickel with silicon and aluminum, while graphite and boron nitride are used as solid lubricant components.

The formation of the structure of such compositions largely depends on the technological parameters of spraying, which determine the temperature and velocity of the particles, the degree of their melting and oxidation, the nature of their interaction with the substrate surface, as well as the porosity and structural homogeneity of the resulting coating. The crystal lattice parameter is an important indicator of the structural state of the coating and reflects the effects of alloying elements and deposition technology. Its variation depends on the chemical composition, phase

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DOI 10.15588/1607-6885-2026-3-3

transformations, and coating formation conditions, which differ between flame spraying and ion-plasma deposition.

Literature review

The effectiveness of gas turbine engine sealing coatings is determined by a combination of their structural and operational characteristics. Studies [1, 2] have shown that the performance of such coatings depends on abradability, wear and heat resistance, porosity, phase composition, and structural stability at elevated temperatures. Maintaining the stability of the metallic matrix and solid lubricant components during operation is also of considerable importance.

The deposition technology has a significant influence on coating structure formation. Studies [3, 4] have established that particle temperature and velocity, the degree of particle melting and oxidation, as well as the cooling rate determine the porosity, structural heterogeneity, phase composition, and level of residual stresses. Therefore, flame spraying and ion-plasma deposition can produce different structural states of the coating even when the initial chemical composition is identical.

Authors [5–7] investigated the effect of small yttrium additions on heat-resistant nickel-based materials. The authors established that Y affects diffusion processes and the formation of oxide layers, while its segregation at grain boundaries and phase boundaries can modify the kinetics of high-temperature oxidation. At the same time, the modification effect depends on the yttrium concentration, since an rise in its content may be accompanied by the formation of Y-containing phases and increased structural heterogeneity.

For MCrAlY coatings, studies [8–10] established a relationship between yttrium content, the structural and phase state of the material, and the formation of a protective Al_2O_3 layer. The authors showed that the distribution of Y-containing phases affects diffusion processes, oxidation kinetics, and the stability of the resulting oxide layer.

Authors [11–14] devoted to heat-resistant nickel-based materials also demonstrated the influence of small Y additions on structural processes and resistance to high-temperature oxidation. It was shown that the effect of alloying is determined not only by the yttrium concentration but also by the initial material composition and the conditions of structure formation.

However, in most studies [5–14], the effect of yttrium has been evaluated mainly in terms of oxidation kinetics, phase composition, and oxide-layer morphology. Changes in the crystal lattice parameters of nickel-based sealing coatings depending on small Y additions and the deposition method remain insufficiently investigated. Therefore, determining the crystal lattice parameters of KNA-82 coatings containing 0.1, 0.3, and 0.5 wt.% Y, produced by flame spraying and ion-plasma deposition, is a relevant materials science task [15].

Objective

The purpose of this study is to establish the regularities of the influence of yttrium concentration within the range of 0.1–0.5 wt.% and the deposition method on the crystal lattice parameters of the KNA-82 sealing coating. To achieve this purpose, it is necessary to determine the interplanar spacings and crystal lattice parameters of the investigated coatings, establish the nature of their changes with increasing yttrium content, and perform a comparative evaluation of the results obtained for flame spraying and ion-plasma deposition. The evaluation criteria are the magnitude and nature of changes in the crystal lattice parameters depending on the Y concentration and the coating deposition technology.

Materials and methods

For the study, KNA-82-based sealing coatings with different yttrium concentrations (0.1%, 0.3%, and 0.5%) were prepared. The base KNA-82 coating, which is widely used at PJSC Motor Sich, contains nickel as the base component, silicon, aluminum, and solid lubricants (graphite and boron nitride).

The coatings were deposited to a thickness of up to 5 mm on one side of cubic specimens made of the nickel-based alloy EI435 (KhN78T). Two deposition methods were used: flame spraying and plasma spraying. These methods were selected due to their widespread industrial application and significant differences in coating structure formation.

Flame spraying is characterized by lower particle heating and cooling rates, which promotes the formation of more equilibrium structures with a lower defect density. Plasma spraying, in contrast, provides high heating and cooling rates, resulting in the formation of metastable structures with a high concentration of defects and microstresses.

X-ray diffraction analysis was performed using CuKα radiation with a wavelength of $\lambda = 1.5418$ Å. The initial experimental table contains the positions of the diffraction peaks (2θ), as well as the calculated interplanar spacings and lattice parameters. The Wulff–Bragg law was used to determine the interplanar spacing:

$$n\lambda = 2d_{hkl} \sin\theta, \quad (1)$$

де n – diffraction order ($n = 1$ in the calculations);
λ – wavelength of the X-ray radiation;
d_{hkl} – interplanar spacing;
θ – Bragg angle, equal to half of the measured 2θ angle.

The crystal lattice parameter, a, for the cubic system was calculated using the following equation:

$$a = d_{hkl} \cdot \sqrt{(h^2+k^2+l^2)}, \quad (2)$$

де h, k, l – are the Miller indices of the corresponding crystallographic planes. For the comparative analysis, two characteristic calculated lattice parameters presented in the

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DOI 10.15588/1607-6885-2026-3-3

initial dataset were used. Values of approximately 3.51 Å obtained in the intermediate calculations were not included in the final plots, since the summary table of the initial dataset used for the concentration analysis contains two lattice parameters of approximately 4.05 and 4.23 Å.

Results

Based on the X-ray diffraction analysis, the crystal lattice parameters of KNA-82 coatings containing 0.1, 0.3, and 0.5 wt.% yttrium, produced by flame spraying and ion-plasma deposition, were determined. The obtained values are presented in Table 1.

Table 1 – Crystal lattice parameters of the KNA-82 coating depending on yttrium content and deposition method

Y content, wt.%	Ion-plasma, parameter 1, Å	Ion-plasma, parameter 2, Å	Flame-sprayed, parameter 1, Å	Flame-sprayed, parameter 2, Å
0,1	4,0525	4,2297	4,0555	4,2353
0,3	4,0537	4,2323	4,0519	4,2322
0,5	4,0543	4,2332	4,0567	4,2356

For the ion-plasma coatings, a consistent increase in both crystal lattice parameters was observed with increasing yttrium concentration. Parameter 1 increased from 4.0525 Å at 0.1 wt.% Y to 4.0537 Å at 0.3 wt.% Y and to 4.0543 Å at 0.5 wt.% Y. A similar trend was observed for parameter 2, with corresponding values of 4.2297, 4.2323, and 4.2332 Å.

The most pronounced changes in the lattice parameters of the ion-plasma coating occurred when the Y concentration increased from 0.1 to 0.3 wt.%. Within this range, parameter 1 increased by approximately 0.0012 Å, while parameter 2 increased by approximately 0.0026 Å. With a further increase in yttrium content to 0.5 wt.%, the increments decreased to approximately 0.0006 and 0.0009 Å, respectively. Thus, the intensity of the structural changes decreased after reaching a yttrium concentration of 0.3 wt.%.

For the flame-sprayed coatings, a non-monotonic variation in the lattice parameters was observed. As the yttrium concentration increased from 0.1 to 0.3 wt.%, parameter 1 decreased from 4.0555 to 4.0519 Å, while parameter 2 decreased from 4.2353 to 4.2322 Å. A further increase in Y content to 0.5 wt.% resulted in an increase in these parameters to 4.0567 and 4.2356 Å, respectively. Therefore, both parameters reached their minimum values at 0.3 wt.% Y.

A comparison of the two deposition methods demonstrates substantial differences in the response of the crystal lattice parameters to yttrium addition. The ion-plasma coatings exhibit a more regular and predictable concentration dependence, characterized by a gradual increase in both parameters and a decrease in the rate of their variation above 0.3 wt.% Y. In contrast, the flame-sprayed coatings show a more complex non-monotonic dependence, with a distinct minimum at 0.3 wt.% Y.

The obtained results indicate that the deposition method is an important factor controlling the structural state of KNA-82 coatings. The differences between two coating types may be associated with different thermal conditions of particle heating and cooling, oxidation during deposition, and the formation of residual stresses. These technological factors can affect the distribution of alloying elements and the resulting crystal structure of the coating.

Among the investigated compositions, 0.3 wt.% Y is of particular interest for the ion-plasma coating. The major change in the lattice parameters occurs before this concentration is reached, whereas a further increase in yttrium content to 0.5 wt.% produces a considerably smaller change. Therefore, based on the observed lattice-parameter trends, the ion-plasma KNA-82 coating containing 0.3 wt.% Y can be considered the most rational composition within the investigated concentration range.

Discussion

The established regularities indicate a significant influence of the deposition technology on the structural state of the KNA-82 coating. Ion-plasma deposition is characterized by a more consistent variation in the crystal lattice parameters with increasing yttrium concentration. Such a dependence indicates more stable and predictable structure formation compared with flame spraying.

The most pronounced structural changes during ion-plasma deposition are observed within the range of 0.1–0.3 wt.% Y. After reaching 0.3 wt.% Y, a further increase in yttrium concentration to 0.5 wt.% is accompanied by a considerably smaller change in the lattice parameters. This may indicate that the structural state of the coating approaches a certain level of stabilization, at which further Y addition no longer causes a proportional change in the investigated parameters.

The effect of yttrium on the lattice parameters should be considered comprehensively. Due to the limited solubility of Y in the nickel matrix, the observed changes cannot be attributed solely to the direct substitution of Ni atoms by Y atoms. They may be associated with the redistribution of alloying elements, changes in the phase composition, crystal lattice defects, and the level of internal stresses.

The flame-sprayed coating exhibits a more complex structural response to yttrium addition. The decrease in the lattice parameters at 0.3 wt.% Y followed by their increase at 0.5 wt.% Y may be associated with the specific thermal conditions during spraying, different degrees of particle melting and oxidation, cooling rates, and the formation of residual stresses. The combined effect of these processes may result in greater structural heterogeneity of the flame-sprayed coating.

From a materials science perspective, 0.3 wt.% Y in the ion-plasma coating is of particular interest. The major changes in the crystal lattice parameters occur before this

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DOI 10.15588/1607-6885-2026-3-3
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concentration is reached, whereas a further increase in Y content produces a considerably smaller structural effect. Therefore, increasing the yttrium concentration to 0.5 wt.% does not provide a proportional change in the coating structure in terms of the investigated structural criterion.

Thus, among the investigated variants, the ion-plasma KNA-82 coating containing 0.3 wt.% Y can be considered the most rational in terms of the observed changes in the crystal lattice parameters. Ion-plasma deposition provides a more regular structural response, while a concentration of 0.3 wt.% Y corresponds to the point beyond which further alloying results in a substantial decrease in the intensity of structural changes. To conclusively confirm the technological advantages of this composition, the X-ray diffraction results should be correlated with data on wear resistance, abradability, heat resistance, and the high-temperature stability of the coating.

Conclusions

It was established that the yttrium concentration within the range of 0.1–0.5 wt.% and the deposition method significantly affect the crystal lattice parameters of the KNA-82 sealing coating.

For ion-plasma coatings, a consistent increase in the crystal lattice parameters is observed with increasing Y content, whereas for flame-sprayed coatings, the dependence is non-monotonic.

The most pronounced structural changes during ion-plasma deposition occur when the yttrium concentration increases from 0.1 to 0.3 wt.%. A further increase in Y content to 0.5 wt.% is accompanied by a significantly smaller rise in the lattice parameters.

The ion-plasma deposition method provides a more regular and stable variation in the structural parameters of KNA-82 compared with flame spraying.

Based on the structural analysis, the ion-plasma KNA-82 coating containing 0.3 wt.% Y was identified as the most rational variant among those investigated, since a further increase in the yttrium concentration to 0.5 wt.% does not result in a proportional change in the crystal lattice parameters.

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Received 20.08.2026
Accepted 14.09.2026
Published 30.09.2026

УДК 621.438:621.793

ВПЛИВ КОНЦЕНТРАЦІЇ ІТРІЮ ТА СПОСОБУ НАНЕСЕННЯ НА ПАМЕТРИ КРИСТАЛІЧНОЇ ҐРАТКИ УЩІЛЬНЮВАЛЬНИХ ПОКРИТТІВ КНА-82

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Мета роботи. *Встановити закономірності зміни параметрів кристалічної ґратки ущільнювального покриття КНА-82 залежно від концентрації ітрію 0,1–0,5 мас. % та способу нанесення – газополуменевого й іоноплазмового – і визначити діапазон легування, за якого структурні зміни є найбільш керованими.*

Методи дослідження. *Параметри ґратки визначали за результатами рентгенівської дифрактоскопії з використанням CuKα-випромінювання (λ = 1,5418 Å). Міжплощинні відстані розраховували за законом Вульфа–Брегга, а параметри кубічної ґратки - за індексами Міллера дифракційних максимумів. Вихідні дифракційні кути та розрахункові значення взято з експериментальної таблиці.*

Отримані результати. *Для іоноплазмових покриттів зі збільшенням Y від 0,1 до 0,5 мас. % обидва аналізовані параметри зростають: 4,0525→4,0543 Å та 4,2297→4,2332 Å. Для газополуменевих покриттів залежність немонотонна: при 0,3 мас. % Y спостерігається локальне зменшення до 4,0519 та 4,2322 Å, після чого при 0,5 мас. % значення зростають до 4,0567 та 4,2356 Å. Найбільша відмінність між способами нанесення зафіксована для 0,3 мас. % Y.*

Наукова новизна. *Встановлено закономірності впливу концентрації ітрію 0,1–0,5 мас. % на параметри кристалічної ґратки покриття КНА-82. Показано, що характер структурних змін суттєво залежить від способу нанесення покриття. Отримані результати дозволяють обґрунтувати раціональний вміст ітрію з урахуванням технології напилення.*

Практична цінність. *Отримані результати можуть бути використані для вибору раціонального вмісту ітрію в покритті КНА-82 залежно від способу його нанесення та необхідних структурних характеристик.*

Ключові слова: *ущільнювальне покриття, КНА-82, ітрій, параметр кристалічної ґратки, рентгенівська дифрактоскопія, газополуменеве напилення, іоноплазмове напилення, газотурбінний двигун.*

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DOI 10.15588/1607-6885-2026-3-3