

Influence of Yttrium Content and Its Application Methods on the Thermal Coefficient of Linear Expansion of KNA 82 Alloy Sealing Coatings: Experimental Studies and Analytical Modeling

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Abstract. This study investigates the influence of yttrium content (0.1, 0.3, and 0.5 wt.%) and deposition methods on the coefficient of linear thermal expansion (CTE) of KNA-82 sealing coatings. Dilatometric measurements were conducted at 20–950°C, followed by regression analysis. The ion-plasma coating containing 0.3 wt.% yttrium exhibited stable thermal expansion behavior at 800–900°C and the highest linear regression fit ($R^2 = 0.898$). In contrast, the corresponding gas-flame coating showed a sharp decrease in CTE at 900°C and pronounced nonlinear behavior ($R^2 = 0.039$). The results suggest that ion-plasma coatings containing 0.3 wt.% yttrium have potential for high-temperature sealing applications. Further microstructural and thermal cycling investigations are required to confirm their long-term performance.

Keywords: sealing coatings, thermal expansion coefficient, yttrium, ion-plasma coating, thermal stability, gas turbine engines, KNA-82

Introduction

The current stage of global aero-engine development is characterized by intense competition in enhancing the energy efficiency and environmental safety of power units. A priority objective is the radical improvement in the efficiency of gas turbine engines (GTEs), which directly reduces specific fuel consumption and the carbon footprint [1]. One of the most critical factors determining the magnitude of losses along the turbine flow path is gas leakage through the radial gap between the rotor blade tips and the inner stator surface. It has been demonstrated that minimizing this gap is the most effective design approach to increase efficiency; however, this requires ensuring the stability of the sealing's geometric parameters throughout the entire engine life cycle. [2].

During GTE operation, complex transient modes arise from thermal expansion of components, centrifugal forces, and gyroscopic loads, leading to dynamic fluctuations in the gap magnitude. Under such conditions, there is a risk of direct mechanical contact (rubbing) between the rotor and the stator. To prevent emergency situations and protect expensive turbine blades, specialized sealing coatings are employed in modern practice [3]. These materials possess a unique architecture that allows them to readily abrade or deform upon contact with the blade (low cutting energy), thereby ensuring the formation of the smallest possible gap without damaging the rotor components.

However, the functioning of such coatings is complicated by several contradictory operational requirements [4, 5]. In addition to high abrasivity, the material must demonstrate exceptional erosion resistance to the impact of high-velocity gas flow saturated with fine abrasive particles. With the increase in gas temperature before the turbine to levels of 1150 °C and above, characteristic of new-generation engines, the problem of thermochemical stability comes to the forefront. Traditional nickel-graphite or nickel-aluminum systems, which are widely used at temperatures up to 900 °C, are unsuitable for extreme conditions. [6]. At temperatures exceeding 1100 °C, high-temperature gas corrosion processes are activated, leading to intensive formation of monoxides and complex spinel compounds. This results in "oxidation" of the coating surface, loss of its abrasibility properties, and premature failure due to erosive wear. To overcome these challenges, the development of new composite compositions alloyed with active elements is critically important, among which yttrium (Y) plays a key role. The introduction of yttrium into the coating system (e.g., a NiCrAlY-type coating) fundamentally alters the oxidation mechanism [7].

Yttrium promotes the segregation of a stable Al_2O_3 phase, which forms a dense, continuous oxide film with high adhesion to the substrate. This prevents oxygen diffusion into the coating and mitigates the negative effects of sulfur in the fuel, thereby ensuring material integrity during prolonged exposure at 1150 °C and above [8]. However, in addition to chemical stability, the coating's viability critically depends on its thermomechanical compatibility with the substrate material. In this context, determining and optimizing the coefficient of linear thermal expansion (CTE) is particularly relevant. Due to the porous structure and complex phase composition of Sealing coatings can have CTEs that differ significantly from those of the superalloys used to manufacture the stator casing [9].

Thermal expansion generates significant internal stresses at the "substrate-coating" interface during thermal cycles (take-off-flight-landing). This causes the development of microcracks, material fatigue, and ultimately results in complete delamination of the abrasible layer. Thus, the development of novel heat-resistant Sealing coatings require a comprehensive approach that combines yttrium alloying for chemical protection with

precise control of thermophysical properties, particularly the Coefficient of Thermal Expansion (CTE), to ensure mechanical durability. Research into the influence of yttrium content on the structure, phase composition, and thermal expansion of abradable materials is a necessary step toward creating reliable radial-gap control systems for prospective aviation GTEs [10, 11]. The aim of this study is to investigate the influence of yttrium content (0.1, 0.3, and 0.5 wt%) and coating deposition technology (gas-flame and ion-plasma spraying) on the temperature dependence of the coefficient of linear thermal expansion of KNA-82 sealing coatings. Particular attention is paid to identifying compositions exhibiting stable thermal expansion behavior in the high-temperature range of 800–900°C and evaluating the applicability of linear regression models to the obtained experimental data.

1. Research methodology

For the studies, KNA-82 coatings up to 5 mm thick were applied to cubic nickel alloy KhN78 T samples. The coating composition included a nickel base with additions of silicon (1.4–2.5%), aluminum (0.3–1.2%), boron nitride (7–13%), graphite (1.5–2.5%), and yttrium (0.1%, 0.3%, or 0.5%) [12–14]. The yttrium content was varied to 0.1–0.5%, as such concentrations promote the stabilization of oxide films, improve coating adhesion to the base material, enhance the thermal stability of alloys, and retard the coagulation of strengthening phases, thereby collectively improving operational characteristics. Coatings were applied by two methods: an ion-plasma method using a plasma installation with argon and nitrogen at a current of 400–450 A, a voltage of 40–50 V, and a surface distance of 100–120 mm; and a gas-flame method employing rod technology, oxygen (4.0–5.0 atm), acetylene (0.8–1.2 atm), and a surface distance of 80–100 mm. For plasma spraying, a mechanical mixture was prepared from powders of nickel (97.5–98.0%), silicon (2.0–2.5%), and urea (10%), which was mixed in a special mixer for 8 hours with the addition of yttrium. The mixture was annealed in a dissociated ammonia atmosphere at 950°C for 4–4.5 hours, followed by the addition of boron nitride, graphite, and aluminum. For gas-flame spraying, the powder mixture was combined with sodium silicate and formed into 4.5 mm-diameter, 400–600 mm-long rods. Before coating application, the samples were thoroughly prepared by cleaning with oil, emulsion, and dirt, degreasing in an etching bath, and blasting with electrocorundum to ensure adequate adhesion of the coating to the substrate.

The dynamics of volumetric changes and possible structural-phase transformations in the material of the developed coatings were analyzed using a Chevenard differential dilatometer (Fig. 1).



Fig. 1 – Photo of the Chevenard dilatometer setup

The maximum heating temperature in the dilatometer furnace was 1000°C. A Type K thermocouple was used for temperature measurement, in conjunction with a PED-250 electronic automatic potentiometer. The electronic differential head comprised a mechanical differential. The unit for measuring and recording the relative change in sample length allowed for direct recording of the length increment $\Delta l = l_x - l_{ref}$ onto a chart recorder. Samples for the studies were prepared with dimensions of 3.5×50 mm.



Fig. 2 – Samples for investigating the coefficient of linear thermal expansion

Dilatometric curves were recorded under conditions of programmed uniform heating at a rate of 10-15°C/min within the temperature range of 20...950°C. The Chevenard dilatometer used an SN differential head, with magnifications $K_x = 145.3$ along the temperature axis and $K_y = 319.25$ along the ordinate axis. A "Piros" alloy sample was used as a reference, possessing known coefficients of linear thermal expansion across the entire temperature range and exhibiting no phase transformations. The true coefficient of linear thermal expansion was determined by graphical differentiation of the obtained curves using a mirror ruler, followed by calculation using the formula:

$$\alpha_{ex} = \alpha_r \pm \frac{K_1}{K_2} (\alpha_r - \alpha_q) \frac{dy}{dx}$$

where α_r - is the average expansion factor of the reference;

α_q - average expansion coefficient of quartz;

K_1, K_2 - optical magnification coefficients of the device along the X and Y coordinate axes;

dy, dx are the dimensions of the catheters in mm of a rectangular triangle on the dilatogram in the temperature range where α_{ex} is calculated.

Processing of experimental data and construction of mathematical models were performed using the Python programming language with the libraries pandas (for data structuring and preprocessing), NumPy (for numerical operations), and scikit-learn (for implementing machine learning methods).

To model the dependence of the coefficient of linear thermal expansion (CTE) on temperature, a linear regression was used. Models were built separately for each yttrium content value (0.1; 0.3; 0.5%) and for each coating application method (gas-flame and ion-plasma), which allowed for obtaining a set of independent approximation dependencies within the investigated subsamples.

The quality of the constructed regression models was evaluated using the coefficient of determination (R^2), which measures the proportion of the variation in the dependent variable explained by the model. Formally, this indicator is defined as follows:

$$R^2 = 1 - \frac{\sum_{i=1}^n (y_i - \hat{y}_i)^2}{\sum_{i=1}^n (y_i - \bar{y})^2}$$

where y_i are the experimental values,

$\hat{y}_i$ are the values predicted by the model,

$\bar{y}$ is the mean value of the sample.

Since the temperature dependence of the coefficient of linear thermal expansion may exhibit nonlinear behavior, the coefficient of determination was used not only to evaluate the goodness of fit but also to identify coating compositions for which linear approximation is insufficient. Particular attention was paid to the gas-flame coating containing 0.3 wt.% yttrium, for which a pronounced decrease in CTE was observed at elevated temperatures. Such behavior requires separate consideration of possible nonlinear effects and the limitations of the selected regression model.

The coefficient of determination ranges from 0 to 1, with higher values indicating a better fit of the model to the experimental data. The use of this criterion enables an objective comparison of approximation quality across different coating compositions and their application technologies within a unified analytical framework.

2. Results and discussion

For gas-flame coatings of various compositions, characteristic features of the temperature dependence of CTE are observed.

The coating with 0.1% Y composition shows the largest difference in CTE values and extrema, with significant oxidation observed after the third heating, indicating insufficient thermal stability and low resistance to cyclic thermal loads.

The coating with 0.3% Y composition is characterized by a gradual increase in CTE from $5.04 \times 10^{-6} \text{ K}^{-1}$ at 100°C to maximum values in the $700\text{--}800^\circ\text{C}$ range. A characteristic feature is the attainment of a maximum of approximately $14.49 \times 10^{-6} \text{ K}^{-1}$ at 800°C , followed by a sharp decrease to $3.45 \times 10^{-6} \text{ K}^{-1}$ at 900°C . Such a sharp decrease in CTE in the high-temperature region may indicate structural changes or phase transformations, potentially leading to additional internal stresses during operation under variable-temperature conditions.

The pronounced decrease in CTE from approximately $14.49 \times 10^{-6} \text{ K}^{-1}$ at 800°C to $3.45 \times 10^{-6} \text{ K}^{-1}$ at 900°C indicates a strongly nonlinear temperature dependence for the gas-flame coating containing 0.3 wt.% yttrium. This behavior explains the extremely low coefficient of determination ($R^2 = 0.039$) obtained using linear regression. Consequently, a simple linear model cannot adequately describe the thermal expansion behavior of this composition over the entire investigated temperature range.

The observed deviation may be associated with structural rearrangements, relaxation of internal stresses, or temperature-induced phase transformations. However, the available dilatometric data do not allow unambiguous identification of these mechanisms. Further microstructural and phase investigations are therefore required to clarify the origin of this behavior.

The coating with 0.5% Y composition demonstrates a monotonic increase in CTE from $4.97 \times 10^{-6} \text{ K}^{-1}$ at 100°C to a maximum value of $9.54 \times 10^{-6} \text{ K}^{-1}$ at 800°C , followed by an insignificant decrease to $8.98 \times 10^{-6} \text{ K}^{-1}$ at 900°C . The more stable CTE behavior at high temperatures and the absence of sharp extrema on the curve indicate greater thermal stability of the coating with 0.5% yttrium content, which is an advantage under cyclic thermal loads.

The CTE curves for gas-flame coatings with 0.3% and 0.5% Y compositions exhibit a similar pattern of change, which is attributed to the common nickel matrix of these materials. Such similarity in temperature dependencies indicates compatibility in the coatings' thermomechanical properties, an important factor in ensuring their operational reliability.

Research into ion-plasma coatings of the KNA-82 system with varying degrees of yttrium alloying showed significant differences in CTE characteristics compared to gas-flame coatings of similar composition.

The coating with a 0.1% Y composition exhibits the lowest CTE across the entire investigated range. The initial value is $5.0 \times 10^{-6} \text{ K}^{-1}$ (at 100°C), with a gradual plateau in the $600\text{--}800^\circ\text{C}$ range at $9.1 \times 10^{-6} \text{ K}^{-1}$. The presence of extrema indicates a high propensity for tensile stresses, which can lead to coating delamination during operation.

The coating with 0.3% Y composition, obtained by the ion-plasma method, is characterized by a stable increase in CTE from $5.7 \times 10^{-6} \text{ K}^{-1}$ to a maximum value of $14.49 \times 10^{-6} \text{ K}^{-1}$ at 800°C . The most significant advantage of this composition is the stability of CTE values in the $800\text{--}900^\circ\text{C}$ range, which minimizes stress gradients at engine operating temperatures. Such thermomechanical stability is critical for improving the coating's durability under cyclic thermal loads. The absence of abrupt changes in CTE within the temperature range of $800\text{--}900^\circ\text{C}$ suggests relatively stable thermal expansion behavior of the ion-plasma coating containing 0.3 wt.% yttrium. This may be associated with the influence of the deposition process on the coating structure and the distribution of alloying elements. Nevertheless, dilatometric measurements alone cannot directly confirm the absence of microstructural degradation or phase transformations. Additional investigations using scanning electron microscopy (SEM) and X-ray diffraction (XRD) are required to establish the relationship between the coating microstructure, phase composition, and high-temperature thermal expansion behavior.

The coating with 0.5% Y composition, applied by the ion-plasma method, exhibits the highest CTE values in the medium-temperature range (up to 600°C). The initial value is $6.9 \times 10^{-6} \text{ K}^{-1}$ (at 100°C). A characteristic feature of this composition is the attainment of a maximum CTE of approximately $14.4 \times 10^{-6} \text{ K}^{-1}$ at $700\text{--}800^\circ\text{C}$, followed by a decrease to $13.0 \times 10^{-6} \text{ K}^{-1}$ at 900°C . This decrease may be associated with several competing mechanisms, including structural rearrangements, relaxation of internal stresses, phase transformations, and high-temperature oxidation. The presence of aluminum and yttrium in the coating composition may promote the formation of protective oxide phases, such as Al_2O_3 and Y_2O_3 . However, the formation and relative contribution of these oxides were not directly investigated in the present study. Therefore, the observed reduction in CTE cannot be attributed exclusively to oxidation without additional chemical and phase analysis. The decrease in CTE at high temperatures is a potential risk factor, as it can lead to increased thermal stresses during cyclic temperature changes.

A comparative analysis of ion-plasma and gas-flame KNA-82 coatings with different yttrium contents revealed that the coating application method significantly influences the CTE characteristics and, consequently, the operational stability of the abrasion layers.

The ion-plasma coating with a 0.3% Y composition exhibits the optimal CTE characteristics, ensuring a stable increase in the expansion coefficient across the entire temperature range without sharp extrema or jumps, indicating the structural stability of the material. It is fundamentally important that in the high-temperature region (800-900°C), where the aircraft engine operates, the CTE curve shows stable values. This minimizes the thermal stress gradient, significantly reducing the risk of delamination and cracking of the abrasion layer.

In contrast to the gas-flame coating of similar composition (0.3% Y), which exhibits a sharp drop in CTE at 900°C, the ion-plasma coating shows more stable behavior at high temperatures, thereby enhancing its thermomechanical stability under cyclic thermal loads.

The coating with 0.5% yttrium content, applied by the ion-plasma method, although demonstrating high CTE values, shows a tendency for the expansion coefficient to decrease at 900°C. This may indicate oxidative processes and potential structural degradation during prolonged exposure at high temperatures.

Coatings with 0.1% yttrium content, whether applied by gas-flame or ion-plasma methods, exhibit the worst CTE characteristics and are least suitable for use under cyclic thermal loads.

The results of constructing linear regression models for the dependencies of CTE on temperature for gas-flame (y_1) and ion-plasma (y_2) coatings at different yttrium content values (0.1; 0.3; 0.5%) are presented in Fig. 3.

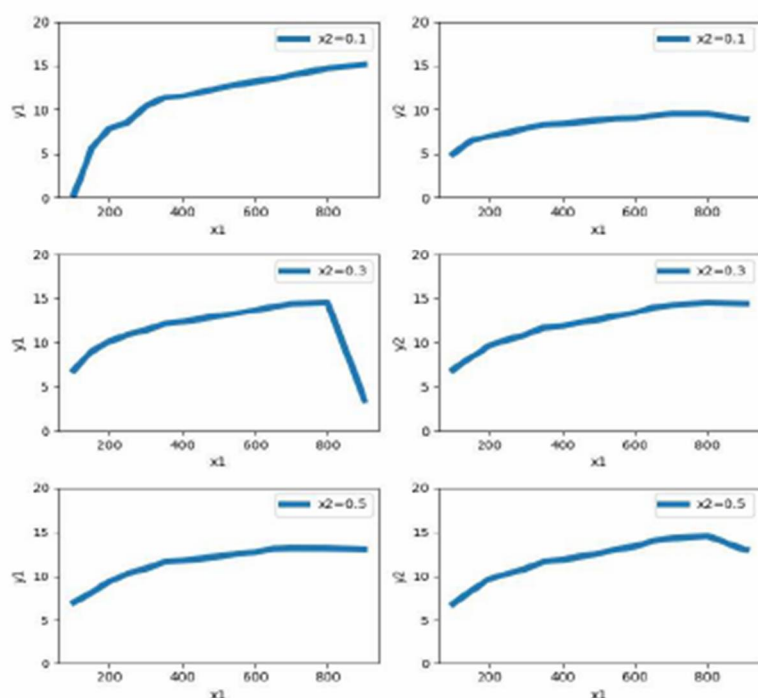


Fig.3 – Linear regression dependencies of CTE on temperature for gas-flame (y_1) and ion-plasma (y_2) coatings at different yttrium contents (0.1; 0.3; 0.5%)

Figure 3 illustrates the temperature dependence of CTE for gas-flame and ion-plasma coatings with different yttrium contents. The experimental curves demonstrate that both yttrium concentration and deposition technology affect the character of thermal expansion.

For the gas-flame coating containing 0.3 wt.% yttrium, a pronounced decrease in CTE at 900°C results in a substantial deviation from the linear trend. In contrast, the corresponding ion-plasma coating exhibits a gradual increase in CTE followed by relatively stable values in the high-temperature region. These differences are reflected in the coefficients of determination presented in Fig. 4.

It should be emphasized that the coefficient of determination characterizes the agreement between the experimental data and the selected regression model. A higher R^2 value does not independently demonstrate superior structural stability or operational durability.

A quantitative assessment of the quality of the constructed models, based on the coefficient of determination (R^2), is presented as a heatmap in Fig. 4.

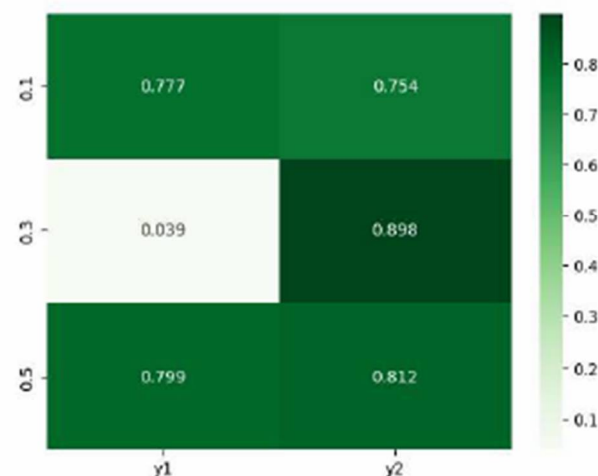


Fig. 4 – Matrix of R^2 coefficient of determination values for linear regression models of CTE depending on yttrium content and coating application method

As shown in Fig. 4, the coefficient of determination depends on both yttrium content and coating deposition technology. For gas-flame coatings containing 0.1, 0.3, and 0.5 wt.% yttrium, the R^2 values are 0.777, 0.039, and 0.799, respectively. The corresponding values for ion-plasma coatings are 0.754, 0.898, and 0.812.

The largest difference between the two deposition methods is observed for coatings containing 0.3 wt.% yttrium. The gas-flame coating exhibits a very low R^2 value of 0.039 due to its pronounced nonlinear thermal expansion behavior, particularly the sharp decrease in CTE at 900°C. In contrast, the ion-plasma coating with the same yttrium content demonstrates the highest R^2 value of 0.898 among the investigated compositions.

For coatings containing 0.1 and 0.5 wt.% yttrium, the differences between the two deposition technologies are less pronounced in terms of linear approximation quality. These results indicate that the effect of deposition technology on the temperature dependence of CTE varies with yttrium concentration.

Conclusions

The experimental investigation of KNA-82 sealing coatings containing 0.1, 0.3, and 0.5 wt.% yttrium demonstrated that both yttrium concentration and deposition technology significantly influence the temperature dependence of the coefficient of linear thermal expansion within the investigated temperature range.

The ion-plasma coating containing 0.3 wt.% yttrium exhibited a gradual increase in CTE from approximately $5.7 \times 10^{-6} \text{ K}^{-1}$ at 100°C to $14.49 \times 10^{-6} \text{ K}^{-1}$ at 800°C, followed by relatively stable values up to 900°C. In contrast, the gas-flame coating with the same yttrium content showed a pronounced decrease in CTE from approximately $14.49 \times 10^{-6} \text{ K}^{-1}$ at 800°C to $3.45 \times 10^{-6} \text{ K}^{-1}$ at 900°C.

Regression analysis revealed substantial differences in the applicability of linear models. The highest coefficient of determination ($R^2 = 0.898$) was obtained for the ion-plasma coating containing 0.3 wt.% yttrium, whereas the corresponding gas-flame coating exhibited a very low R^2 value of 0.039, indicating strongly nonlinear behavior.

The relatively stable high-temperature CTE behavior of the ion-plasma coating containing 0.3 wt.% yttrium suggests its potential suitability for high-temperature sealing applications. However, further investigations of microstructure, phase composition, thermal cycling resistance, and coating–substrate compatibility are required to confirm its long-term operational performance.

The obtained results provide an experimental basis for further optimization of the composition and deposition technology of KNA-82 sealing coatings intended for gas turbine engine applications.

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