Виконано аналіз підвищення ефективності турбін авіаційних двигунів шляхом вдосконалення складу ущільнювальних покриттів, що застосовуються в лабіринтних ущільненнях. Встановлено, що до таких покриттів висувається ряд суперечливих вимог, щодо їх властивостей на початковому етапі обкатки двигуна і при подальшій експлуатації. Показано основні види пошкоджень зазначених покриттів застосовуваних у конструкції лабіринтних ущільнень в процесі експлуатації газотурбінних двигунів. В зв'язку з необхідністю підвищення температури газів в турбіні авіаційних двигунів запропоновано додатково легувати серійні покриття на нікелевій основі ітрійвміщуючими лігатурами.

Наведено результати дослідження впливу легування ущільнювальних покриттів, що приробляються, на експлуатаційні властивості в умовах впливу високотемпературного газового потоку. Визначено, що найбільш раціональним є легування серійного покриття КНА-82 багатокомпонентною лігатурою Co-Ni-Cr-Al-Y.

Встановлено, що застосування розробленого покриття в діапазоні температур 1100...1200 °С дозволяє знизити питомі витрати палива авіаційних двигунів за рахунок підвищення коефіцієнта корисної дії турбіни, а також запобігти зношуванню торцевих поверхонь гребінців лабіринтного ущільнення ротора. На підставі моделювання плину потоку в зазорі лабіринтного ущільнення чисельним методом показано, що застосування розроблених матеріалів покриттів в конструкції ущільнень турбіни компресора і вільної турбіни дозволяє знизити величину витоку охолоджуючого повітря в проточну частину турбіни за рахунок зменшення зносу гребінців лабіринтних ущільнень ротора

Ключові слова: газотурбінний двигун, коефіцієнт корисної дії, радіальний зазор, лабіринтне ущільнення, легування, витрати газу

UDC 62-762: 669.247
DOI: 10.15587/1729-4061.2018.140912

STUDYING AND DESIGNING IMPROVED COATINGS FOR LABYRINTH SEALS OF GAS-TURBINE ENGINE TURBINES

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1. Introduction

Improvement of operation effectiveness of present-day aircraft gas turbine engines (GTE) is one of important tasks of aircraft engine building [1, 2]. Gas turbine engine efficiency coefficient (EC) is improved by a number of measures. These include improvement of aerodynamic profiles of compressor and turbine, combustion processes, hot engine parts cooling and reduction of losses from gas flow leaks in compressor and turbine stages.

It is known that improvement of seal designs is one of effective ways of improvement of operation efficiency of the GTE as a thermal engine [3]. Considering that the main gas flow between the compressor and turbine stages occurs through radial clearances, much attention is paid to their minimization in designing the GTE. However, there are several factors creating necessity of forming radial clearances between the GTE stator and rotor parts, particularly, rotor imbalance and vibration, misalignment of supports and uneven thermal expansion of rotor and stator parts during engine operation, especially in transient-state conditions. Moreover, size of these clearances should be kept as small as possible during the entire period of GTE operation taking into consideration changes in its operating conditions.

To reduce size of the radial clearance, various kinds of wearing-in sealing coatings are widely used. During operation, they can harmlessly contact the labyrinth seal and blade. Such seals enable formation of a minimum clearance between the rotor and the stator. Thus, development of sealing coatings that could easily wear-in at the initial stage of engine operation and permanently maintain geometry of their worn contour between overhauls at temperature 1,100–1,200 °C is a relevant task.

2. Literature review and problem statement

When new aircraft engines are designed or existing models upgraded, special attention is paid to improvement of their efficiency coefficient. The results obtained in a study of the effect of radial clearance in turbomachines on efficiency of their operation were presented in [4, 5]. It was shown that the radial clearance between the rotor and the stator significantly affects efficiency of compressors and turbines. However, the measures being developed to reduce clearances are related to improvement of the GTE design while the issues of improvement of a wearing-in coating composition are ignored. It was established for a PS-90A type engine [6] that leakage into the turbine air-gas channel of one percent of cooling air tapped after the high-pressure compressor results in a 0.3 % increase in specific fuel consumption. It was shown in the same paper that leakage of cooling air into the main stream, especially into the high-speed region, can bring about additional EC losses. For example, leakage into the axial clearance between the nozzle diaphragm and the turbine wheel can result in EC losses of up to 1.5 % per each percent of cooling air leakage of the stage. The results of these studies indicate necessity of maintaining radial clearances at the lowest possible level.

To solve this problem, it was proposed in [7] to reduce radial clearance between the stator and the rotor which would make it possible to solve the problem of improving the GTE efficiency in a most rational way. The authors of this study have suggested measures to increase GTE efficiency based on modernization of the rotor blade design while the change of radial clearance values resulting from the stator-rotor interaction remains unexplored and not taken into consideration. This approach does not allow one to fully realize potentials of the GTE turbine and, accordingly, cannot provide an essential increase in its EC.

Thus, reduction to a possible minimum of gas and cooling air leaks is one of the most important and most significant problems of the GTE design. Obviously, for its effective solution, all means should be involved including improvement of design, manufacturing techniques and the materials used. In turn, analysis of the studies shows that the main attention is given currently to the design of turbomachines. The problem of minimizing gas leaks is solved by reducing residual rotor imbalance by means of brush seals and compensators. Such measures will increase the engine EC but will require new engineering and technology solutions for their realization. This results in an alteration of the GTE design, its price rise and cannot be realized for the already engineered and in-service engines. Analysis of published data shows that the issue of development of a material science approach to solving the task of air leakage suppression by improving materials of the labyrinth seal coatings is not elucidated in literature. At the same time, such situation significantly limits possibilities of modernization of gas turbines in service.

Labyrinth seals (LS) are widely used in turbines of modern and prospective GTEs to reduce cooling air leaks (Fig. 1). They are used both to reduce internal (interstage) and external (terminal) gas leaks and in gas-oiling protection systems.

Radial clearances between the rotor and stator of the GTE turbine have a significant effect on the GTE efficiency [5] but they gradually change in the course of continuous operation. In this connection, maintaining of the required level of radial clearances during the warranty period of engine operation and their minimization in a cruising regime are realized in a number of works, for example [4], by using active control systems. Being an effective measure of reduction of gas leaks, application of such systems for existing gas turbine engines is hard. Also, this approach does not take into consideration the sealing coating composition depending on the operating conditions of engine parts.

a *b*

Fig. 1. Covering disk of the GTE turbine, the TV3-117 family: general view (*a*); the labyrinth seal ridges (*b*)

Sealing coatings based on nickel and solid lubricant are widely used currently in building gas turbine engines. Mechanical properties of wearing-in sealing coatings were evaluated in [8] and it was established that the coating hardness is an effective indicator for evaluating coating abradability and makes it possible to avoid full-scale tests at the initial study stage. However, issues concerning control of the coating hardness at main stages of the GTE life cycle remain unresolved. Authors of [9] have shown that composition and further behavior of the coating significantly affect wear of the rotor parts with temperature change. At the same time, they did not substantiate an optimum coating composition from the standpoint of the rotor wear resistance. Rigorous sealing coating service conditions lead to various types of damages described in [10 13]. Service conditions have predetermined a number of contradictory requirements to coatings. On the one hand, to prevent seizure or intensive wear of the rotor elements at the initial stage of engine operation, coating must be well worn-in and, accordingly, have a low hardness. On the other hand, to maintain minimum clearances in the seal and thereby ensure required output performance of the gas turbine engine, coating must have a high erosion resistance under the influence of an aggressive gas flow. That is, the material must have ability of hardening during a long period of operation. It is also necessary to ensure a high heat resistance of sealing coatings since an intensive development of high-temperature gas corrosion is possible in the hot engine tract [12]. In addition, this paper reports that M-Cr-Al-Y based coatings are effective in the temperature range up to 850 °C. For higher temperatures, it was proposed to use nickel aluminides and various ceramic materials which can lead to abrasion of the engine parts. Thus, measures should be taken during the coatings development process to differentiate their properties at various stages of operation. At the same time, an approach to development of coatings with physical and mechanical properties that may vary depending on the GTE life cycle was not considered.

Thus, the problem of creating advanced materials for sealing coatings of the hot part of gas turbine engines remains pressing and not solved sufficiently till now. Since nickel-based coatings can be used in a limited temperature range and introduction of a ceramic component results in a still heavier wear of the rotor parts, the resulting wear resistance is optimal for the stage of steady GTE operation. At the stage of wearing-in, high hardness of the coating material results in intensive wear of the rotor parts. Based on the literature data, there is no system engineering of composition of the coating material possessing the properties differentiating depending on the stage of the GTE life cycle. Such materials should be easily worn-in at the initial stage of engine operation and maintain constant geometry of the worn coating contour at temperatures of 1,100...1,200 °C during the period between overhauls. In this case, the main task of designing labyrinth seals is ensuring an acceptable leakage rate through the LS in conditions of forming its compromise clearance size to reduce leaks. It is also necessary to avoid undesirable contacts of the rotor and stator seal parts in unsteady regime of rotor operation and in thermal deformation of parts.

3. The aim and objectives of the study

This study objective was development of high-temperature wearing-in nickel-based sealing coatings with properties varying at different stages of the GTE life cycle.

To achieve the objective, the following tasks were set:

– to analyze the main types of serial produced coating damages;

– to study structure and properties of coatings with various alloying systems;

– to calculate the gas flow rates through the LS depending on the clearance size in the design of the current turboshaft engine of the TV3-117 family.

4. The study materials and methods

At present, aircraft engine building enterprises of Ukraine widely use nickel-based coatings of KNA-82 type having satisfactory performance at temperatures of 900...950 °C. A further increase in gas temperature to 1,100...1,200 °C will lead to a catastrophic development of gas corrosion and coating deterioration. In this regard, to solve the problem of increasing endurance of sealing coatings, it was suggested to additionally dope the KNA-82 coating with various yttrium-containing master alloys: monocomponent yttrium (Y), Ni–Y composition and Co–Ni–Cr–Al–Y multicomponent composition. The choice of yttrium is explained by its availability and positive influence on structural stability and morphology of inclusions as well as a decrease in liquation heterogeneity and a number of other positive effects. The amount of yttrium introduced must ensure formation of Y_2O_3 oxide film which improves gas corrosion resistance.

To assess the doping effect on wearing-in and resistance to aggressive action of heated gas streams, coatings of four compositions were examined (Table 1). Coatings were applied on specially prepared samples by gas-flame method. A high-temperature nickel alloy was used as the base material. Previously, a sub-layer based on aluminum and chromium was applied to the samples. It provided better adhesion of the coating material to the substrate as well as a smoother transition of the temperature coefficient of linear expansion [14].

The coating structure was examined with the help of Zeiss Axio Observer optical microscope at a 200–800 magnification. Microhardness was determined with LECO AMH 43 USA microhardness meter in accordance with the requirements of GOST 9450-76 at a load of 10 g.

Table 1

Composition of the starting material and yttrium content, % by weight

Coating composition No.	Composition	Yttrium content, %		
		Master alloy	Blend	Coating
1	KNA-82+Ni–Y master alloy	18.4	0.3	0.3
2	KNA-82+pure yttrium	99	2.3	2.1
3	KNA-82+ Co–Ni–Cr–Al–Y master alloy	0.7	0.1	0.1
4	KNA-82: powdered KNA and VKNA, serial technology	–	–	–

Erosion resistance was assessed using TF 21-11 sandblast unit. The coating surface was exposed to a stream of silicon oxide with grain size of 63...80 (GOST 3647-80) at an angle of 90° at a pressure of 0.5 atm. The value of erosion wear was determined by the deepest point after which erosion wear resistance of the samples was compared.

Heat resistance of coatings was evaluated by relative increase in their weight after holding the samples in an oven at 1,100 °C for 50 and 100 hrs. The samples were pre-degreased and weighed on analytical scales before and after testing which allowed us to obtain relative values of heat resistance.

Simulation of flow in the labyrinth seal clearance of the compressor turbine and free turbine of the turboshaft GTE of the TV3-117 family was carried out by the finite element method in a manner similar to that described in [15]. The CFX module of the ANSYS software complex was used. The Menter SST "k–ω" model was chosen as a model of turbulence due to its higher accuracy and reliability for the class of flows with a positive pressure gradient in profile streamlining [16].

The height and profile of ridges of the gas-turbine labyrinth seals were evaluated after running time using the LaserGauge Automation measuring system, model 1101, with accuracy not less than 0.01 mm.

5. Results obtained in the study of structure, properties and efficiency of use of improved sealing coatings

Labyrinth seals in the compressor turbine and the free turbine of GTE of the TV3-117 family are used both for minimizing inter-stage gas flows and sealing the oil cavities (Fig. 2).

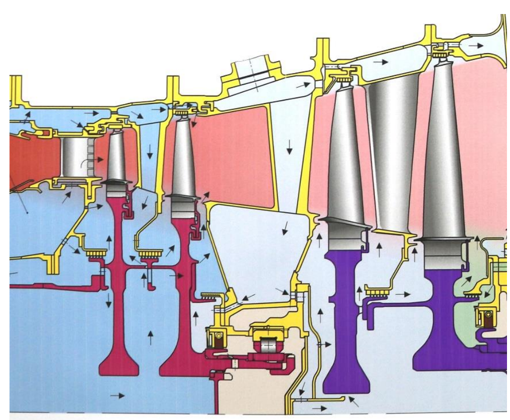


Fig. 2. Diagram of cooling the compressor turbine and the free turbine of GTE of the TV3-117 family

The required clearance in the LS is ensured at the stage of manufacture of the GTE or its repair by turning operation (Fig. 3, *a*). During the engine service time, especially at the wearing-in stage, wear of both LS ridges and coating takes place. During routine maintenance of the GTE, visual examination of the nozzle diaphragm is carried out. It has been established that the inner surface of the KNA sealing coating had traces of coarse incision and touching with preservation of the sealing coating in depressions (Fig. 3, *b*). This is connected to the displacement of the GTE rotor caused both by the error of mounting the rotor supports and the rotor imbalance.

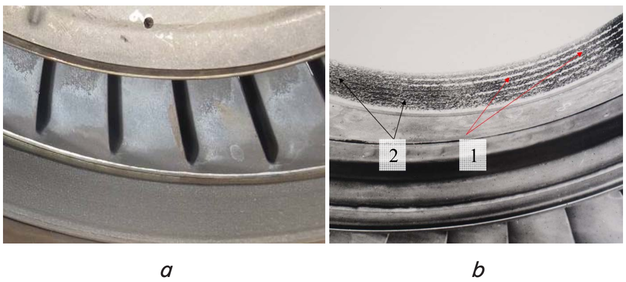


Fig. 3. Physical appearance of KNA-82 coating: after machining (*a*); after operating time (*b*); traces of intensive incision (1, 2), traces of touching (3, 4)

In the process of development of a coating working in a contactless LS of the GTE, its hardness is subject to conflicting requirements. On the one hand, the coating material should have a minimum hardness and, accordingly, minimum wear resistance. This requirement is determined by the necessity of ensuring possibility of coating wearing-in during the GTE running-in phase. Taking into account beating of the GTE rotor as well as its possible imbalance, especially in the transient modes of engine operation, contacting of the LS ridges with coating is possible at this stage and thus its wearing-in. Low coating hardness in this case ensures wearing-in of the coating material with no change of the ridge geometry. Given the small edge radii and thickness of the LS ridges, their wear during the initial stage of the GTE operation can lead to an increase in gas leaks through the LS and, as a result, a decrease in efficiency of the turbine and GTE in general. There were cases of abrasion of the LS ridges and a significant change of their geometry during operation of engines of the TV3-117 family.

Defects in the KNA-82 coating were observed during the GTE operation. They were caused by low wear resistance of this coating. Mainly, they are cracks, cavities, spalls, discontinuity. Also, erosion wear (Fig. 4, *a*), partial peeling (Fig. 4, *b*) and chipping of the coating (Fig. 4, *c, d*) may appear in a post-operation period. Chipping may be caused by mechanical impacts during assembly or operation.

Thus, the experience of practical use of sealing coatings in the non-contact LS and analysis of requirements to them show that their wear resistance should be minimal at the stage of the GTE running-in. This ensures wearing-in of the coating and ridges of labyrinth seals taking into account their beating and imbalance of the GTE's rotor.

At the stage of engine operation, wear resistance of the coating should be raised to ensure its long-term and reliable operation while ensuring stability of gas leakage and, as a consequence, specific parameters of the gas turbine engine. Stability of the LS clearance also provides reduction of the amount of cold air discharged into the air-gas channel of the turbine thus increasing its efficiency and fuel efficiency of the engine in general.

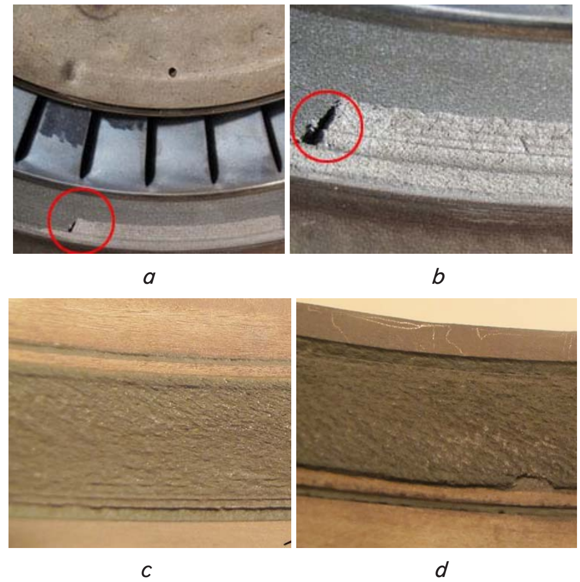


Fig. 4. Defects of the LS coatings: peeling (*a, b*); erosion wear (*c*); spall (*d*)

It was shown in [17] that coating of KNA-82 type additionally doped with yttrium can meet the described operating conditions. As was shown in [18], its main distinction from the serial coating is the emergence of additional intermetalloides Ni_3Al, Co_2Al_5, $CoCr_2$ in the coating of composition No. 3 and Ni_5Y in compositions Nos. 1, 2. With a further high-temperature exposure, considerable amounts of oxides appear which provide increase in coating hardness.

It was established by coating microstructure examination that application of yttrium-containing master alloys leads to a change in pore size observed in the microsection plane (Fig. 5). As can be seen from Fig. 5, coatings of compositions Nos. 1, 2, 3 (Fig. 5, *a–c*) are characterized by pores of considerably smaller size in comparison with composition No. 4 (Fig. 5, *d*). The most uniformly distributed pores were in the coating of composition No. 3 and their size was the smallest. Probably, in the future, in the process of wearing-in, formation of the most uniform contour of incision will be realized for compositions with the smallest pore size. In this case, load on the surface will be distributed evenly and there will be no "tearing-off" of particles from the coating surface in the LS and no coating interaction will take place.

As already mentioned above, in order to meet all requirements to the material, its properties must alter during operation. It was found that improved coatings had sufficiently low microhardness at the initial stage which grew significantly in the process of high-temperature action (Fig. 6). This is probably due to the fact that coatings have a significant amount of pores and a small content of oxides and intermetalloides at the initial state [18]. Some difference in coating hardness is obviously because of presence of oxides (Al_2O_3, Y_2O_3) and intermetalloides (Ni_5Y, NiAl, Ni_3Al, Co_2Al_5, $CoCr_2$) in the doped coatings.

A significant increase in microhardness after a high-temperature exposure at 1,100 °C for 50 and 100 hrs is a consequence of intense formation of oxides of both simple and spinel type: $NiCr_2O_4$, $CoAl_2O_4$. Also, the change in microhardness is associated with an increase in the amount of intermetalloide phases. It was found that the highest microhardness level corresponded to the coating of composition No. 3. Thus, from the point of view of operation, this nature of microhardness variation is the most advantageous since during the stage of wearing-in when the coating interacts with the LS ridges or the turbine blades, they will undergo less intensive wear as compared with the coatings of serial production. With the further extension of the GTE service time, high hardness will ensure maximum preservation of the formed profile and the coating in general.

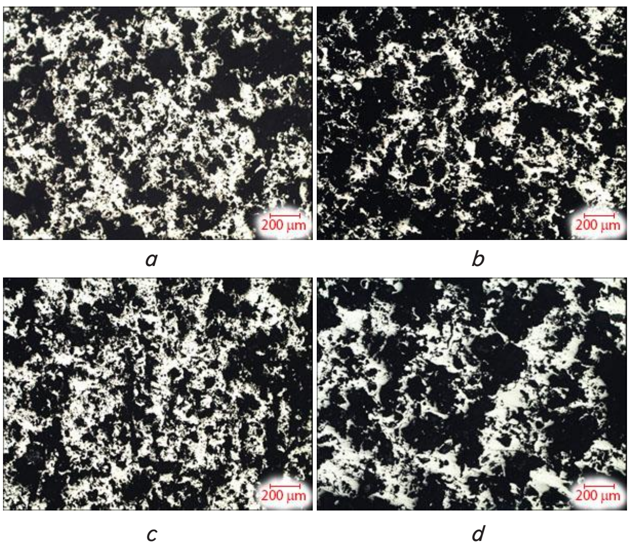


Fig. 5. Microstructure of LS coatings after their application: composition No. 1 (*a*); composition No. 2 (*b*); composition No. 3 (*c*); composition No. 4 (*d*)

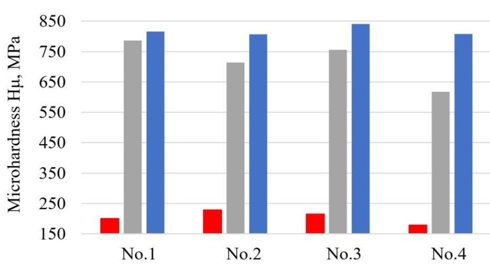


Fig. 6. Dependence of coating microhardness on the content of master alloys and the time of holding at 1,100 °C: KNA-82+NiY (No. 1); KNA-82+Y (No. 2); KNA-82+CoNiCrAlY (No. 3); serial KNA-82 (No. 4); ■ – initial, ■ – 50 hrs, ■ – 100 hrs

Considering that spalling can occur in the process of the rotor - stator interaction under the action of tangential loads on the coating, an estimate of the ultimate detachment strength of coatings was made (Fig. 7). It was found that coatings of compositions No. 1 and No. 3 had the highest adhesion strengths. This is probably due to formation of the most optimal phase ratio in the coating material and provision of better adhesion interaction between the base material and the coating.

Evaluation of resistance of the coating material to erosive effects has made it possible to elucidate that doping has a significant influence on erosion resistance (Fig. 8). The greatest erosion resistance was observed for coatings of compositions No. 2 and No. 3 which was confirmed by the results of measuring their hardness. Thus, it can be assumed that these coatings will have higher resistance to gas erosion during the GTE operation. This fact is probably connected to the formation of dense oxide films and spinels at the surface of these coatings which not only improve erosion resistance but also positively affect heat resistance of the coating material.

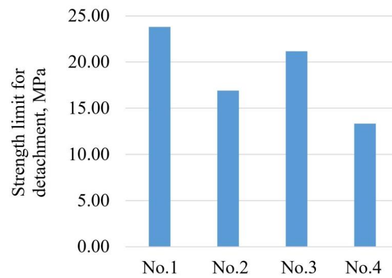


Fig. 7. Dependence of ultimate detachment strength on the master alloy content (VZh-102 is the base): KNA-82+Ni-Y (No. 1); KNA-82+Y (No. 2); KNA-82+Co-Ni-Cr-Al-Y (No. 3); KNA-82 (No. 4)

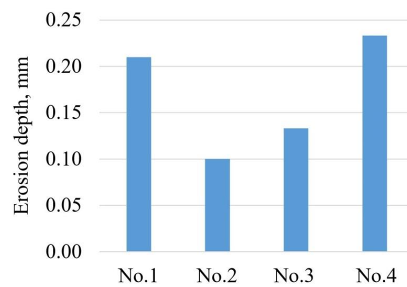


Fig. 8. Dependence of the coating erosion resistance on the master alloy content: KNA-82+NiY (No. 1); KNA-82+Y (No. 2); KNA-82+Co-Ni-Cr-Al-Y (No. 3); KNA-82 (No. 4)

Because unsatisfactory heat resistance of coatings leads to their rapid destruction and growth of the radial clearance in the LS, influence of doping with yttrium-containing master alloys on heat resistance of nickel-based coatings has been established. The obtained data have shown that the complex master alloy Co-Ni-Cr-Al-Y and pure yttrium (Fig. 9) had the highest resistance to gas corrosion. It was also found that oxidation processes were most active in the first 50 hrs of testing. Further, the rate of formation of corrosion products reduces.

As was established in [18], in the coating of composition No. 3 the amount of double oxide $NiCr_2O_4$ increases and the amount of NiO phase decreases during holding.

Spinel $NiCr_2O_4$ is a sufficiently stable oxide phase and its formation on the coating surface positively affects resistance to gas corrosion. The Al_2O_3 oxide film which is also formed during the oxidation process has a high density and satisfactorily protects the coating surface from further negative effects of the corrosive medium at elevated temperatures. In turn, formation of this film prevents seizure between the coating and the counter-body [19]. Introduction of yttrium to coating and formation of oxides Y_2O_3 also increase resistance to gas corrosion. In addition, introduction of yttrium leads to a decrease in oxygen activity in the surface layer and the formed film serves as a barrier for further oxidation.

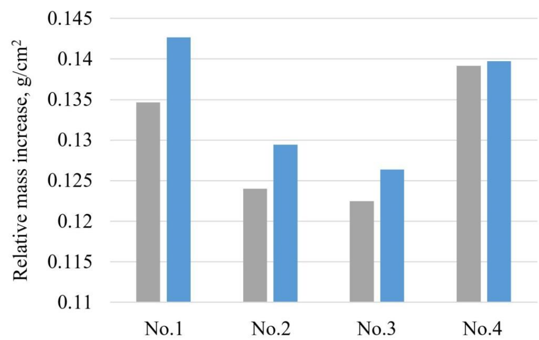
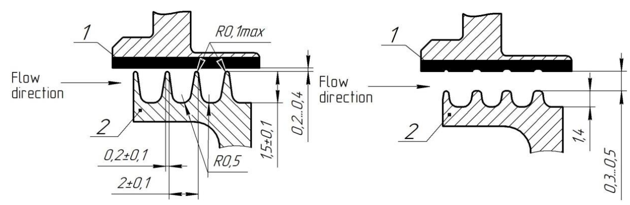


Fig. 9. Change of the sample mass after 50 and 100 hrs of holding at 1100 °C: KNA-82+NiY (No. 1); KNA-82+Y (No. 2); KNA-82+CoNiCrAlY(No. 3); KNA-82 (No. 4); — 50 hrs, — 100 hrs



a *b*

Fig. 10. Seal of the GTE turbine, the TV3-117 family: nominal (*a*); worn out (*b*); KNA sealing coating (1); turbine rotor ridges (2)

The change of the flow regime from laminar to turbulent one results in a sharp growth of wave resistance and as a consequence, a fall of air flow rate. At the same time, maintaining of the nominal clearance and the ridge geometry are the most important factors determining operation efficiency.

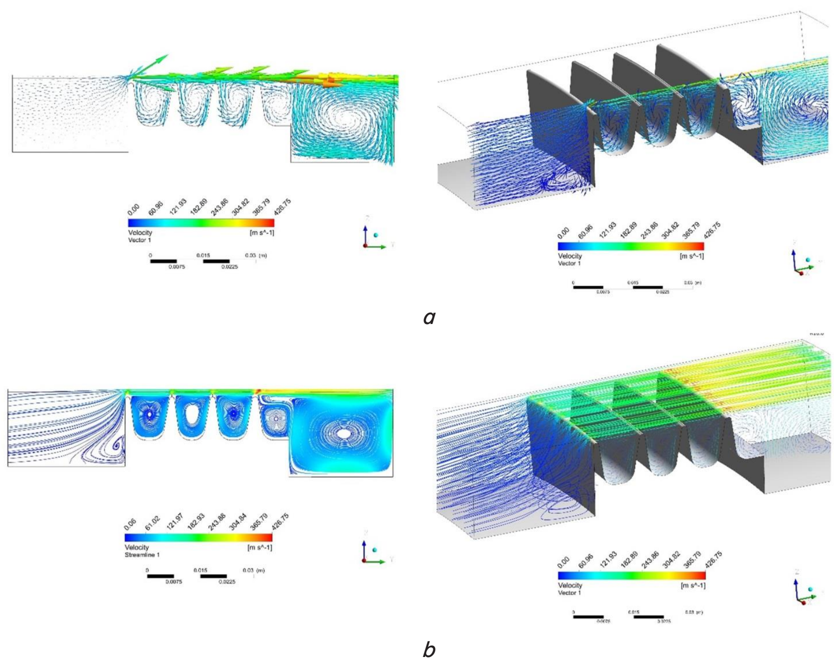


Fig. 11. Lines of flow in the air-gas channel of the labyrinth seal of the GTE compressor turbine, the TV3-117 family, with various clearances in the labyrinth seal (the flow rate is determined by the digital scale): nominal (*a*); increased (*b*)

Thus, it has been established that the coating KNA-82+Co-Ni-Cr-Al-Y fits most fully the working conditions in the design of labyrinth seals of current GTEs.

Sealing coatings of this type are widely used in the design of turbine of turboshaft GTEs of the TV3-117 family for sealing both compressor turbine and free turbine. Therefore, the effect of using an improved coating composition based on a minimal and time-stable radial clearance and hence gas leaks on improvement of fuel efficiency of gas turbine engines will be significant.

To evaluate it, flow in the turbine LS clearance was modeled. A diagram of nominal (*a*) and worn (*b*) 4-ridge labyrinth seal of the turbine of the GTE of the TV3-117 family is shown in Fig. 10.

It is known that the mass gas leakage is the main characteristic of the LS which determines its effectiveness [20]. When gas flows in a sealing with subcritical (subsonic) velocities, flow is determined by A. Stodola's formula [21] based on the idea of total velocity suppression in the chambers and the idea of absence of flow narrowing in clearances which come to resemble a series of nozzles:

$$G = \mu \cdot \pi \cdot D \cdot \delta \cdot \sqrt{\frac{p_1^2 - p_2^2}{z \cdot R \cdot T_1}}, \quad (1)$$

where μ is the flow coefficient taking into account hydraulic resistance and design features of the seal; D is the average clearance diameter; δ is clearance in the seal; p_1 and p_2 are the gas pressures respectively in front of the labyrinth, on the high pressure side, and behind the labyrinth; z is the number of ribs of the labyrinth seal; R is the gas constant; T_1 is the gas temperature in front of the seal.

The main effect of the seal type under the study is achieved by means of reducing air flow through the seal clearance with flow breakaway and appearance of vortex phenomena (Fig. 11).

The initial data for calculating the gas flow rate through the LS of the GTE compressor turbine and the free turbine, the TV3-117 family, are shown in Table 2.

As a result of measuring the LS ridge profiles of a group of the GTEs that were in operation for 790–1,000 hrs, it was established that the ridges were worn out by 0.1...0.12 mm in height. Taking into account wear of the sealing coating, the average radial clearance in the seal was 0.3 mm.

Study of the established dependence of gas flow through the engine LS has shown (Fig. 12) that the maximum influence on the turbine efficiency was exerted by the LS of the first and second stages of the compressor turbine. This is explained by maximum temperature and pressure gradient at these stages of the turbine.

The total gas flow rate through all labyrinth seals of the compressor turbine and the free turbine at nominal clearances of 0.2 mm was 0.9 kg/s. Wear of the LS ridge tops increased the radial clearance and, as a result, the total gas flow rate increased up to 1.35 kg/s. Taking into account that the air flow rate through the TV3-117 GTE compressor was about 8.7 kg/s, it can be seen that the gas leakage was 10.3 % at nominal clearances in the LS. The spread of radial LS clearances caused by wear of ridge tops has resulted in gas leakage growth up to 15.5 %.

Table 2

Initial data for calculating the gas flow rate through the labyrinth seals of the GTE compressor turbine and free turbine, the TV3-117 family

Parameter	Labyrinth seal (stage/turbine)			
	1st st./CT	2nd st./CT	1st st./FT	2nd st./FT
Coefficient of gas flow rate [21]	0.7	0.7	0.7	0.7
Average diameter of clearance, mm	212	206	186	198
Gas pressure in front of the labyrinth seal, MPa	0.95	0.48	0.16	0.10
Gas pressure behind the labyrinth seal, MPa	0.57	0.26	0.1	0.09
Number of ridges in the labyrinth seal, pc.	4	5	8	5
Gas temperature in front of the labyrinth seal, K	623	573	523	523

Note: CT=compressor turbine; FT=free turbine

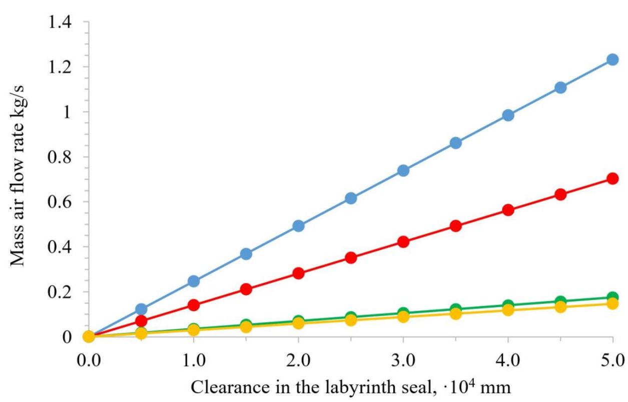


Fig. 12. Dependence of gas flow rate through the labyrinth seal depending on the clearance size: — 1st stage of TC, — 2nd stage of TC, — 1st stage of FT, — 2nd stage of FT

Based on the dependence of increase in specific fuel consumption of the GTE induced by air leakages to the air-gas channel of the turbine, it can be assumed that the increase in the specific fuel consumption of the GTE because of ridge wear will be 0.6 %. For TV3-117 GTE having specific fuel consumption in cruising regime about 0.255 kg/hp·hr, increase in fuel consumption will amount 1.53 10^{-3} kg/hp·hr.

Thus, taking into account that the engine power in cruising regime of operation is 1,500 hp. (1,103 kW), use of improved coatings in the design of labyrinth seal of the compressor turbine and the free turbine will reduce the hourly fuel consumption by 2.3 kg. Given the average annual program of gas turbine engine production and their operating time at an average fuel price of USD 0.9 per kg, the expected savings from the use of advanced coatings are USD 165.600.

6. Discussion of results obtained in the study of improved sealing coatings

The demonstrated results of the study of main defects observed in operation of current GTE wearing-in sealing coatings, such as KNA-82, and features of structure and properties of coatings improved on their basis have shown high efficiency of their use. The rational composition of master alloy selected based on systematic studies of structural features, hardness, adhesion strength and erosion resistance has enabled realization of the idea embedded in the design of GTE labyrinth seals of a new generation: alteration of physical and mechanical properties of the wearing-in coatings at various stages of engine operation.

Unlike the existing and widely used in aircraft engine building compositions of wearing-in sealing coatings, their advanced counterpart makes it possible to maintain at minimum level radial clearances both in the compressor turbine the and the free turbine of the turboshaft engine of the TV3-117 family. Analysis of effectiveness of use of improved KNA coatings in the design of labyrinth seals of the compressor turbine and the free turbine of the turboshaft GTE of TV3-117 family has shown that this measure ensures reduction of the amount of leakage of cooling air into the air-gas channel of turbines and, accordingly, providing a significant economic effect due to a decrease in wear of ridges of labyrinth seals in the rotor part. The use of the developed wearing-in coating operating in the temperature range of 1,100...1,200 °C makes it possible to reduce specific fuel consumption by the GTE, improve the turbine efficiency and prevent wear of the LS ridge end faces of the discs.

Analysis of properties of the developed advanced KNA coating taking into account features of the phenomena occurring in the sealing devices of the radial clearances of the GTE rotor of various types indicates the prospects of their use in the design of both serial and future engines. At the same time, its use to seal radial clearances between the turbine blades and the stator will significantly increase the effect of its use and thus improve their performance characteristics and economic attractiveness.

The results obtained in the studies testify an opportunity of use of advanced nickel-based sealing coatings under conditions of a high-temperature gaseous medium. However, to confirm the findings, it is necessary to carry out field tests on an engine as the set of operation factors can give somewhat different results. Since the obtained results confirm the fact that it is most rational to use Co-Ni-Cr-Al-Y master alloy, it would be advisable to carry out studies to determine the rational amount of this master alloy. This would ensure an opportunity of obtaining better operational properties of the coatings being developed. No less important is the issue of replacing solid lubricants used at present since the use of boron nitride can be limited at such high operating temperatures.

7. Conclusions

1. It was established that the most common defects of serial coatings occurring in the course of operation were erosion wear, peeling and spalling of the coating. Spalling is the result of mechanical damage often observed at the stage of engine assembly and peeling is caused by internal stresses formed in the course of spray application of the coating and

temperature gradients occurring in the engine operation. Erosion wear is associated with insufficient hardness of the coating during operation of the aircraft engine which brings about an increase in radial clearance and, consequently, fuel consumption.

2. It has been established that the use of a coating of the KNA-82+Co-Ni-Cr-Al-Y composition is rational from the point of view of operating conditions in the turbine of GTEs of the TV3-117 family. The coating structure is characterized by a more even distribution of pores and a satisfactory dispersion of the solid phase which makes it possible to form an even contour of blade incision during the run-in phase.

It has been established that before the high-temperature exposure, microhardness of coatings is about 200 MPa and differs not much in coatings of different compositions. Exposure to a temperature of 1,100 °C leads to a more than five-fold increase in coating microhardness. The maximum increase in hardness was observed for the KNA-82+ +Co-Ni-Cr-Al-Y coating. The ultimate detachment strength of coatings with yttrium-containing master alloys was on the average 60% higher in comparison with the serial KNA-82 coating.

It was found that the phases formed in the KNA-82+ +Co-Ni-Cr-Al-Y coating during its spraying and high-temperature exposure exert a noticeable effect on heat resistance, probably due to formation of $NiCr_2O_4$, $CoCr_2O_4$ spinels and dense oxide films on Al_2O_3 and Y_2O_3 base. Their formation makes it possible to improve operational reliability of the GTE parts due to providing higher heat resistance and strength of adhesion of the coating to the matrix.

3. As a result of calculations, dependence of the gas flow rate through the LS on the size of the radial clearance was found. It was established that wear of ridges and increase in the size of clearance led to a growth of the total gas flow rate from 0.9 kg/s to 1.35 kg/s which is equivalent to an increase in gas leakage as high as 15.5 %.

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