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ANALYSIS OF MODERN EXPERIENCE IN DEVELOPMENT OF SEALING COATINGS FOR PARTS OF GAS TURBINE ENGINES (REVIEW)

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ABSTRACT

In the work, the experience in development of sealing thermal coatings for parts of gas turbine engines was analyzed. It was found that the tasks of developing compositions and technologies of thermal spraying of sealing coatings intended to provide the optimal radial clearance between components of stator and rotor in order to reduce the consumption of technological fuel and improve the efficiency coefficient of engines, are relevant. The principles of optimizing the composition of sealing coating material were described. They consist mainly in the combination of ease of plunging a blade into coating with resistance to erosion wear, which provides the operation efficiency of coating with its fatigue life. The temperature modes of operation of sealing coatings in different sections of gas turbine engine were determined. For spraying of sealing coatings applying thermal methods, composite powders are used, the composition of which corresponds to the concept of metal solid lubricant. As a metal component, Ni, AlSi, Ni- and Co-alloys are used and as a solid lubricant, graphite, hexagonal boron nitride, betonite and polyester are used. For high-temperature sections of turbines, a combination of a stabilized zirconium oxide with hexagonal boron nitride and polyester is used. The composition of these combinations determines the temperature zone of their use, related to the working conditions of compressor or turbine.

KEYWORDS: sealing coating, thermal spraying, matrix, solid lubricant, abrasion, erosion resistance, compressor, turbine

INTRODUCTION

Gas turbine engines (GTE) are the main primary engines of powerful compressor and pumping units, the reliability and efficiency of which is paid special attention. Increasing the efficiency of modern GTE is one of the important tasks of modern engine construction. During their manufacture, special attention has always been paid to increasing the efficiency and, accordingly, reduction in fuel consumption. One of the basic parameters of an engine affecting its efficiency, are radial clearances between working blades of turbine (compressor) and stator parts (super rotor inserts) [1]. According to the carried out studies, an increase in relative radial clearance by 1 % leads to a decrease in engine efficiency by about 3 % and fuel consumption by almost 10 % [2]. Since the size of radial clearance between rotor and stator significantly affects the efficiency of turbine, its reduction allows solving this problem in the least expensive way.

This can be achieved by creating a minimal, close to zero radial clearance between the ends of blades and the engine casing and keeping it at a set level throughout the whole engine operating life. However, during operation as a result of the action of gas flow temperatures, deformation of the casing and blades, vibrations of rotor and casing during operation under off-design conditions, twisting of rotor, etc., often a contact of the end part of blades with the engine casing arises. As a result, a significant wear of blades appears, which results in an increase in a radial clearance of the flow tract during operation of the engine, which leads to a decrease in efficiency, reduction in the operating life of blades and sometimes to fracture of parts being in contact [3].

One of the ways of solving the problems of reducing the radial clearance between rotor and stator and increasing the efficiency of GTE turbine are measures based on the modernization of designs of turbomachines, blades, preliminary planned creation of an initial radial clearance, which allows avoiding touching the ends of blades and turbine casing in the operation process. At the same time, the problem of minimizing gas leakage is solved by reducing the residual rotor imbalance, the use of brush seals and compensators. Such measures allow increasing the efficiency of engines, but require new design and technological studies. This leads to a change in GTE design, increasing its cost and cannot be implemented in already designed engines in operation [4].

The most rational method of reducing the size of radial clearance is to use various kinds of sealing run-in coatings, which are easily abrased in the course of operation when interacting with the tips of blades or crests of labyrinths without their further fracture. Sealing or abradable coatings are used in GTE in aircraft, power engineering and gas-pumping units.

Thermal spraying methods allow depositing sealing coatings (instead of inserts from sealing materials), that are so pliable that the edge of a blade or a labyrinth can easily cut into their layer, but at the same time strong enough to withstand the pressure of the gas flow, including at high temperatures.

The aim of the work is to analyze literature data on the conditions of the work, the requirements for the properties of materials, experience in development of compositions of sealing thermal coatings on GTE parts.

FUNCTIONAL PURPOSE OF SEALING COATINGS

The need in creating new sealing materials for GTE is caused by the requirements to reduce the specific fuel consumption. One of the most important tasks set before the developers of challenging GTE, is providing minimum admissible clearances between blades and casings of compressor and turbine to reduce working gas leaks. However, reducing the size of a radial clearance is associated with an increase in wear of blades at the ends and the risk of their breakage as a result of contact with stator.

To avoid breakage and wear of blades, special sealing coatings are developed, which have a number of physical-mechanical and tribotechnical characteristics. The scheme of using sealing coating to adjust clearances in GTE is shown in Figure 1 [5].

The efficiency of using sealing coatings is characterized by contact interaction of rotor and stator of GTE. Ideally, when as a result of interaction of rotor parts with an abradable coating, only the latter is worn, when rotor is shifted, a clearance with an area that is 3 times smaller than in the case of using wear-resistant coating is formed. Since gas consumption is directly proportional to the leakage area, it is obvious that the leakage of gas in the case of using abradable sealing coatings will be approximately 3 times lower than in the case of non-abradable (wear-resistant) coatings [6].

REQUIREMENTS FOR SEALING COATINGS

Based on the functional purpose of run-in sealing coatings, abradability is one of the basic requirements for sealing materials. To satisfy this requirement, it is necessary that the strength of the sealing material was much lower than the strength of the material of blades or crests of a labyrinth. However, the strength of the sealing material determines its erosion resistance, which should be high enough to guarantee operation of the engine during a set life. Since there are two such contradictory requirements set forth to the strength of the sealing material, the choice of its value is the most responsible moment in the development and application of coating.

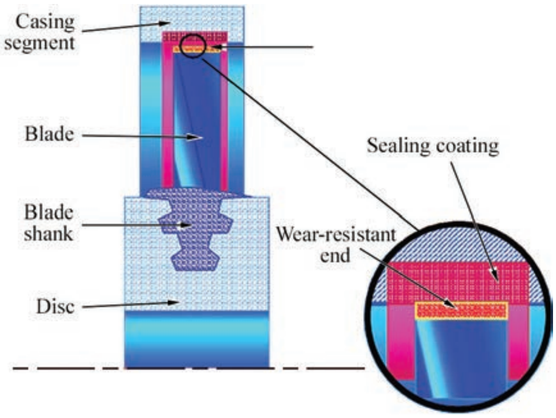

Figure 1. Scheme of application of sealing coating in GTE

The effect of the strength of the sealing material on its abrasion and erosion resistance is shown in Figure 2 [7]. The nature of these dependencies is similar for different materials, but quantitative ratios are different. When constructing these curves, it is implied that the composition of the coating material is maintained and the strength is regulated by changing the structure of the material.

Sealing coatings are used in different areas of GTE, as is shown in Figure 3, and the main criterion for choosing coating material is the operating temperature of the area, on which it is deposited [8].

General requirements (ideally) that abradable sealing coatings should meet, depending on working conditions, are the following [8, 9]:

- running-in of components being in contact;
- sufficient strength but significantly lower than the strength of rotor parts (blades);
- low friction coefficient, which reduces wear in the contact process;
- providing the minimum wear of compressor rotor parts (due to a high abrasion);
- absence of overheating and ignition of parts of titanium alloys as a result of friction (cutting) of rotor with stator;
- high erosion resistance of sealing in the conditions of gas flow with solid particles;
- resistance to cyclic temperature drops;

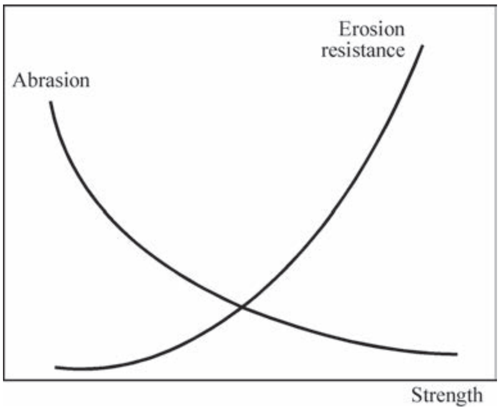

Figure 2. Impact of strength of sealing material on its abrasion and erosion resistance

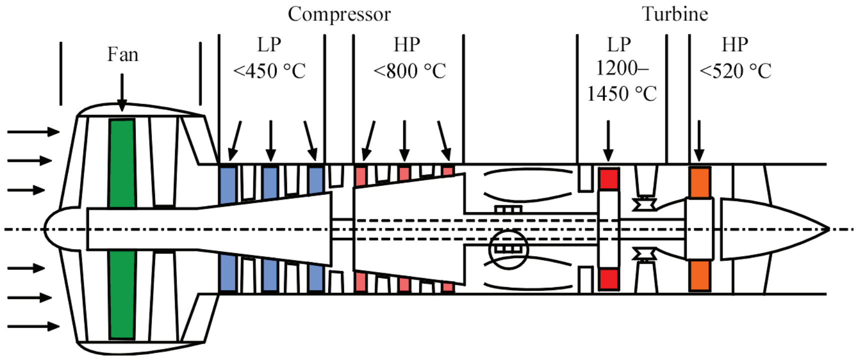

Figure 3. Model of modern turbine with temperature mode of operation of sealing coatings (LP — low pressure; HP — high pressure)

- the coefficient of thermal expansion that provides a reliable joining of abradable material (coating), with stator;
- stability of properties for a long time at operating temperatures;
- chemical resistance to salty water (corrosion), engine fuel, lubricant for hydraulic systems, engine flushing liquids;
- low plunging or contact friction energy;
- lack of transition of material from the surface of abradable seal on the end of blades and vice versa;
- lack of gas leaks due to open porosity in the material;
- low cost and repairability.

Since abradable material is cut by the ends of blades, it is also important that the formed products of wear do not exceed a certain size (0.2–0.3 mm). Larger particles getting into clearances between a rotating part and a sealing material can cause its additional fracture.

An effective operation of sealing coating is provided at the ratio of wear of coating to wear of blade, which is equal to 10:1. But at the ratio of 5:1, the operation of sealing coating is considered quite satisfactory.

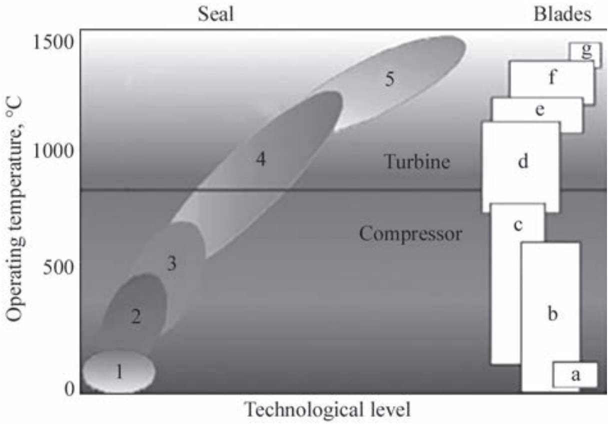

Figure 4. Types of materials for manufacture of seals and blades of GTE, depending on operating temperature: 1 — polymer; 2 — AlSi-polymer; 3 — metal matrix with solid lubricant; 4 — MCrAlY-materials; 5 — ceramics (a — fibrous polymer composites; b —titanium; c — stainless steel; d — super alloys; e — blades produced by directed crystallization; f —monocrystalline blades; g — heat-resistant alloys)

MATERIALS AND METHODS OF DEPOSITION OF SEALING COATINGS

Development and selection of sealing material consists in providing strength characteristics at which abrasion and erosion resistance of material meet the requirements specified under the set working conditions throughout the whole life. As strengthening coatings for GTE parts mostly composite coatings are used, consisting of matrix and fillers (solid lubricants).

The matrix in the coating provides its strength and resistance without leading to excessive wear of blades. As a matrix material in sealing coatings, the following materials are usually used:

- aluminum-silicon materials for low-temperature sections;
- MCrAlY (M = cobalt, nickel or cobalt/nickel) for medium temperatures of compressor sections;
- yttrium-stabilized zirconium (high-temperature ceramic material) for high-temperature turbine sections.

All of them have a strength, lower than in traditional materials (stainless steel, titanium, nickel alloys, etc.) used for the manufacture of GTE blades (Figure 4 [10]).

Depending on the hardness of the matrix material, the mechanism of coatings abrasion during plunging of blades can be of two types: wear with shear and wear with chipping of coating particles (Figure 5) [5]. The first type of wear is typical for coatings, where relatively soft alloys are used as the matrix material, that are subject to shear, such as Al-alloys (Figure 5, *a*). The second type of wear is characteristic of coatings, where, harder alloys are used as a matrix and to remove particles during a contact with a blade, the presence of porosity in the coating is required (Figure 5, *b*).

Solid lubricant or dislocation phase serves as a source of crack formation and propagation, providing the coating with the necessary brittleness, while ensuring that wear products are small enough and can not block cooling channels or provoke further wear of parts [11]. Graphite and hexagonal boron nitride are the materials, that are the most frequently used as a solid lubricant.

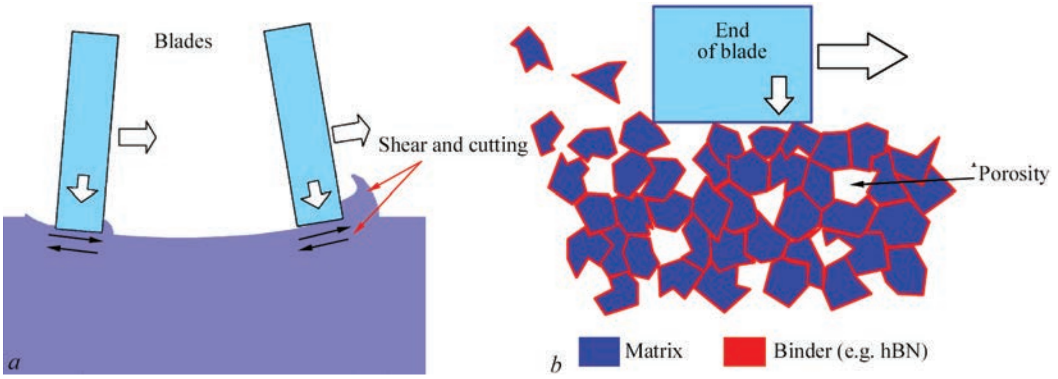

Figure 5. Schemes of wear mechanisms of coatings in contact with blades: *a* — wear with shear and cutting; *b* — wear with chipping

Sealing coatings should also have a certain level of porosity to achieve the desired abrasion. The controlled level of porosity can be achieved by adding the optimal amount of polyester to the sprayed material [12]. During further heat treatment, the polyester evaporates and the desired level of porosity is formed in the coating. Heat treatment of coating is carried out by heating to a temperature of 453–500 °C in air [11, 12]. The number and size of pores determine the abrasion and erosion resistance of coatings. Erosion resistance decreases with increasing porosity, and abrasion increases [12]. Pores and voids are microcrack nuclei between the particles of coating when touching the end of a blade. Due to these microcracks, a clean cut of coating with a minimal transfer of the coating material to the end of a blade occurs [11].

In some cases, sealing coatings require a preliminary spraying of the intermediate layer (sublayer) on the base to increase the adhesion strength. As the sublayer material, 9 5 % Ni–5 % Al is mainly used [8].

As the ranges of operating temperatures and pressures in GTE are very large, different materials and types of abradable coatings are used in them, depending on operating conditions of engine parts, on which they are deposited. The choice of a particular type of abradable coating primarily depends on the operating temperature of the section in which it will be used. Coating systems which are used depending on the operating temperature are shown in Figure 6 [5].

To form sealing coatings on GTE parts, thermal spraying technologies are the most promising and in demand today [13]. For this purpose, compositions of composite powders and flux-cored wires are developed. Coatings of composite powders are sprayed by oxyfuel and plasma spraying methods. The process of plasma spraying is a process with higher temperatures than that of oxyfuel spraying, which means that materials with higher melting temperatures can be deposited using the plasma spraying process. Flux-cored wire coatings are sprayed by oxyfuel and electric arc spraying methods.

By adjusting the thermal spraying modes, it is possbile to control the structure and, accordingly, the properties of produced coatings. Due to this, it is possible to produce sealing coatings with the following types of structures [14]:

- very porous, with many unmelted particles, produced by very careful selection of spraying parameters to achieve the desired degree of abrasion. An accurate reproduction of such coatings can be difficult, and they require a strict control;
- dense and homogeneous coating structures with such additives as polymers, graphite, bentonite and boron nitride (hBN). Abrasion is regulated mainly by the concentration of additives, not by changing spraying parameters, which helps to produce denser coatings with the desired properties.

SEALING COATINGS FOR COMPRESSOR SECTION

AlSi-polyester is a typical sealing coating that is widely used in GTE due to its good abrasion, self-lubrication and thermal conductivity and is the most common coating used in low pressure compressors at low temperatures [15]. The coatings are deposited by the method of plasma spraying of a mixture of powders of aluminum-silicon alloy (Al–12Si) and polyester. The content of aluminum-silicon alloy, which provides structural strength and resistance of the coating to erosion, amounts to about 52 %, and polyester

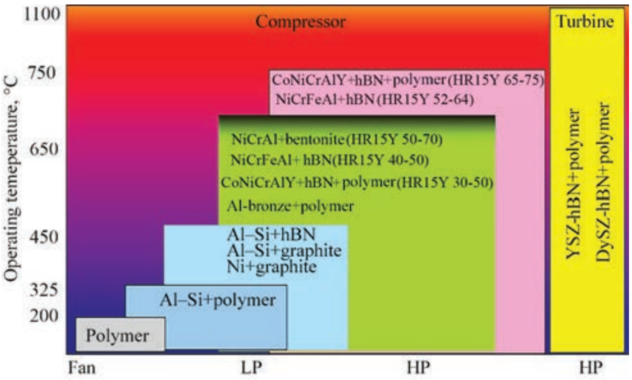

Figure 6. Systems of sealing coatings used for GTE parts depending on the operating temperature

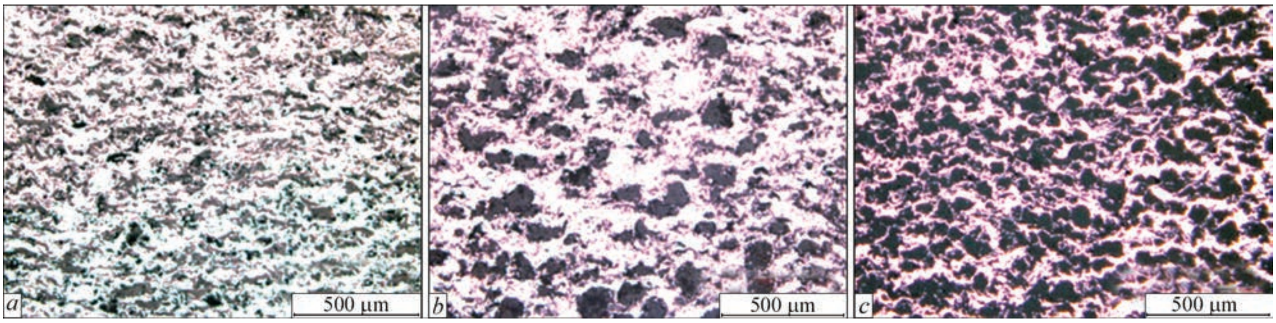

Figure 7. Microstructure of AlSi alloy based coatings with solid lubricant additives: *a* — graphite; *b* — hexagonal boron nitride; *c* — polyester

with self-lubricating characteristics amounts to about 40 %, the rest is a binder. AlSi-polyester sealing coating is mainly used for sealing the casing in the lower and middle parts of compressor with a temperature of up to 350 °C (as a result of temperature limitation of polymer in the coating) [16]. The desired level of porosity of coatings amounts to 2 % with a corresponding Rockwell surface hardness HR15Y 40-50. According to Sulzer Metco [17], coatings of 60Al–12Si–40 polyester, deposited by plasma method, have a hardness HR15Y 65–80 and porosity of 3–5 %.

As fillers, hexagonal boron nitride and graphite are also used. Coatings of Al–8Si-hBN (20 %) + organic binder (8 %) and Al5Si (Al6Si, Al7Si) — graphite (22, 24, 45 %) + organic binder (7, 9, 8 %) are upplied at operating temperatures up to 450–480 °C (due to the temperature limitation of aluminum in the material). The desired level of porosity amounts to 15–20 % with the corresponding Rockwell surface hardness HR15Y 40–50 (40–70 according to Sulzer Metco) [15]. The content of hexagonal boron nitride in the coatings can amount to 40–50 % [9].

Al-bronze alloy is also used [18] as a matrix instead of AlSi alloy. The operating temperature of the coating, taking into account Al (7.5–8.5 %)–Cu (75–85 %) alloy with the addition of polymer (5.0–14.5 %) is up to 650 °C. At operating temperatures above 350 °C, it is necessary to carry out heat treatment of the coating to remove polyester in order to prevent an uncontrolled flash. The coatings are deposited by plasma method. Hardness of coatings amounts to HR15Y 60–70 and the porosity is 6–10 %.

The microstructure of coatings based on AlSi alloy with the addition of polyester, hexagonal boron nitride and graphite is shown in Figure 7 [5].

When using metal matrices with higher melting point and shear strength than in aluminum or its alloys, the coating structure is usually porous to provide its abrasion. Such coatings include coatings of the nickel-graphite system, the structure of which represents a nickel matrix in which lamellar graphite is randomly distributed (Figure 8) [19]. Due to the content of graphite, nickel-graphite composite coatings are also limited in temperature to about 450 °C. The hardness of the nickel-graphite coating varies depending on the ratio of nickel and graphite in it. The content of graphite in the coatings can vary from 15 to 40 %.

For higher operating temperatures, it is advisable to use alloyed Ni in combination with ceramic fillers. An example of coating used in compressor at operating temperatures up to 700 °C is shown in Figure 9 [20]. The structure of the coating consists of NiCrAl matrix, thermostable ceramic dislocation particles and porosity.

NiCrAl-bentonite coatings (Ni–4Cr–4Al–21 % bentonite) have higher heat resistance than AlSi-polyester, AlSi-hBN, AlSi-graphite or Ni-graphite coatings and are successfully used in the high-temperature section of high-pressure compressors at a temperature higher than 500 °C [21]. HR15Y hardness of coatings is 30–60.

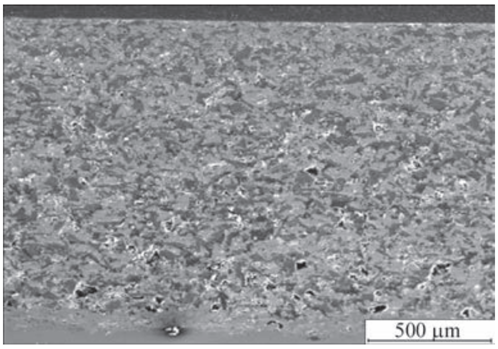

Figure 8. Microstructure of Ni-graphite coating

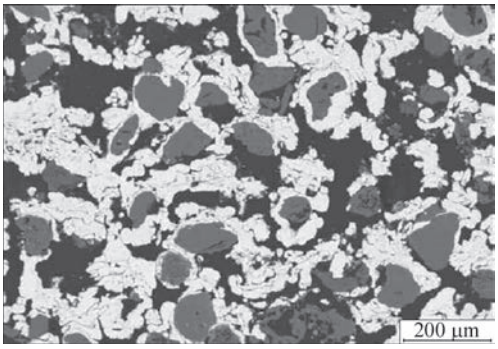

Figure 9. Microstructure of NiCrAl-ceramics coating

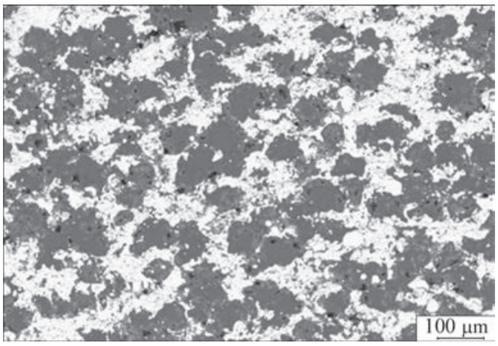

Figure 10. Microstructure of plasma CoNiCrAlY-hBN-polyester coating

During operation of coatings at higher temperatures, it is necessary that the coatings have resistance to erosion and high-temperature oxidation at corresponding operating temperatures. As a metal matrix, in these cases MCrAlY (M = Ni and/or Co) materials are used.

As far as solid lubricant/dislocator should withstand high temperatures hexagonal boron nitride (hBN) is used as a solid lubricant. Coatings are usually produced by the method of plasma spraying. The porosity in the coatings is formed by introducing polyester particles, which are removed from the coating by heat treatment, resulting in formation of porosity in the coating. Figure 10 shows a typical microstructure of plasma coating CoNiCrAlY-hBN-polyester [12].

The content of the components in the coatings is Co(29–30 %)–Ni(24–25 %)–Cr(16 %)–Al(6 %)–Y(0.3 %)-hBN(4, 7 %) + polyester (14–15 %) + organic binder (3 %).

It is strongly recommended that these coatings are subjected to heat treatment after spraying to remove the polymer component and create porosity in the coating structure, improving abrasion. Usually, such coatings have a porosity from 35 to 60 % and a hardness from 65 to 75 when measuring on the Rockwell HR15Y scale. The coating is recommended to be used at temperatures up to 850 °C.

SEALING COATINGS FOR TURBINE SECTION

Similarly to CoNiCrAlY-based coatings described above, modern ceramic sealing coatings consist of three phases: the phase of ceramic matrix, usually zirconium oxide, stabilized by yttrium oxide or dysprosium, polymer and solid lubricant [5, 20, 22]. The polymer can be removed from the coating in the process of heat treatment to create porosity in the coating. As a solid lubricant, hexagonal boron nitride is used. Typical thermal protection coatings have the following composition: 94.5 % YSZ (or DySZ) — 4.7 % polyester — 0.8 % hBN. To protect the metal base from high-temperature corrosion and oxidation, as well as to reduce the difference of the coefficients of thermal expansion between the base and the ceramic layer, a metal MCrAlY sublayer is used. Microstructure of typical sealing coatings based on ceramics with different level of porosity is shown in Figure 11 [5].

Today, at aircraft engineering enterprises of Ukraine, KNA-82 nickel-based coatings with satisfactory service properties at temperatures of 900–950 °C are widely used. A further increase in the temperature of gases to 1100–1200 °C can lead to catastrophic development of gas corrosion and destruction of coating. In this connection, to solve the problem of increasing the resistance of sealing coatings, it was suggested to perform an additional alloying of KNA-82 coating with different kinds of yttrium-contained master alloys: with monocomponent yttrium (Y), Ni–Y composition and multi-component composition of Co–Ni–Cr–Al–Y [23–25]. Figure 12 shows the microstructure of the developed coatings deposited by oxyfuel method [25].

METHODS OF STUDYING THE PROPERTIES OF SEALING COATINGS

As was mentioned earlier, the basic properties of sealing coatings are abrasion and erosion resistance.

The mechanisms of coatings abrasion are very complex, as during contact of the coating with the blade, a combination of cutting, heating, plastic deformation and wear occurs. Therefore, it is extremely difficult to model the service conditions of sealing coating in the laboratory. There are a number of highly specialized installations to determine abrasion used by engine manufacturers and developers of coatings.

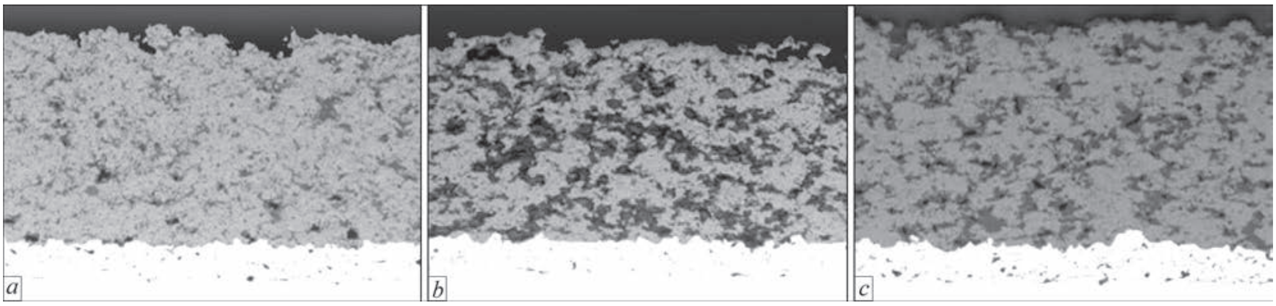

Figure 11. Microstructure (×50) of coatings based on ZrO_2–Y_2O_2 (*a*, *b*) and ZrO_2–Dy_2O_3 (*c*) with different level of porosity, %: *a* — 24; *b* — 43; *c* —30

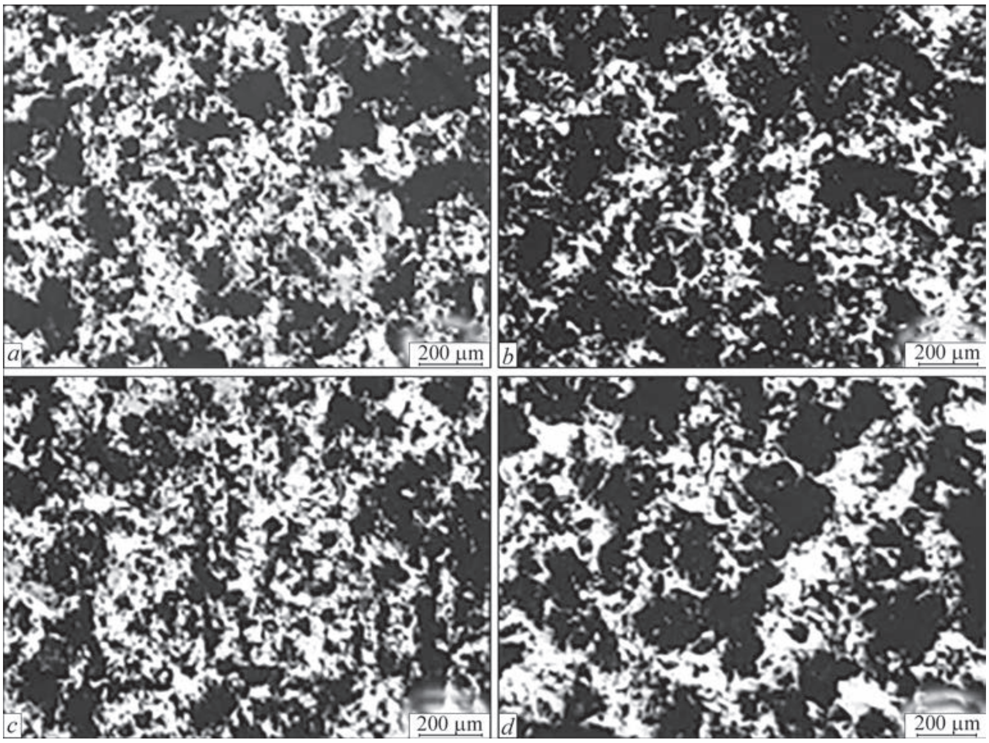

Figure 12. Microstructure of sealing coatings produced by oxyfuel method of spraying: *a* — KNA-82 + master alloy; *b* — KNA-82 + pure yttrium; *c* — KNA-82 + master alloy Co–Ni–Cr–Al–Y; *d* — KNA-82: KNA+VKNA powder (serial technology)

In particular, Sulzer Metco company has one of the installations for testing materials for abrasion (Figure 13), which has proven itself well and is constantly used by manufacturers of engines and companies producing coatings around the world [9].

There are also many self-made testing installations to test coatings abrasion. However, there is still no standardized method to test coatings abrasion and therefore, the results obtained during testing in different installations cannot be compared.

HR15Y hardness tests are to some extent an alternative to a bench test abrasion [26]. To determine the hardness of high-porosity coatings, the used method should have an averaging effect and allow measuring very low hardness. The Rockwell resistance hardness test (HR15Y) is suitable for taking into account these two conditions and is used to measure the hardness of sealing abradable coatings.

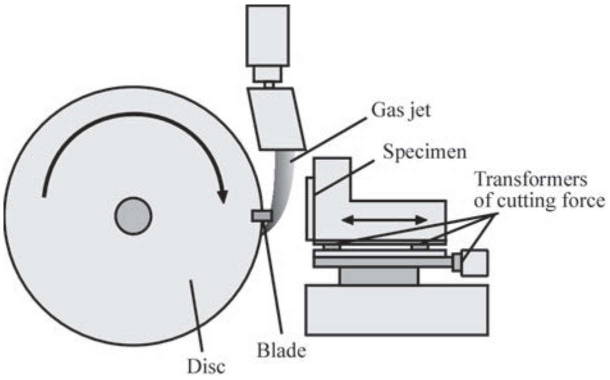

Figure 13. Scheme of installation for high-temperature tests of sealing materials and coatings for abrasion

Erosion tests are carried out according to the standard procedure of quantitative evaluation of the surface of coatings to erosion with the use of a shot blasting machine. The specimen is located 100 mm from the nozzle of the shot blasting machine at an angle of 20°; aluminum oxide with 50 μm particles is used as abrasive [9].

The properties of abradable sealing coatings are determined by their chemical composition, as well as their microstructure. Two coatings with the same chemical composition, but with a very different microstructure, will not behave equally under the same operating conditions. Several studies emphasize the influence of the microstructure of the coating on the effective thermomechanical properties and general characteristics [27, 28]. For example, it is reported that pores and cracks reduce the thermal conductivity of coatings. Determination of the volume content of different structural components of the coating is performed by using the method of image analysis.

The adhesion strength of sealing coatings with the base is determined by the method of tear (ASTM C633) or bending (ASTM B571).

In addition to a good abrasion, heat impact and thermal cycling resistance is another important requirement for sealing coating of compressors and turbines. For strengthening the parts of compressor, the coatings are subjected to tests on thermal cycling by heating to 470 °C with subsequent water cooling. Thermal resistance of the coating under these conditions is resistance determined by the change in the adhesion strength of coatings with the base. As a reference, the adhesion strength of sprayed coating before thermocycling is taken [29].

For ceramic coatings, thermal cycling is carried out in the conditions of furnace heating up to 1150 °C with the subsequent air cooling to 50 °C. The test temperature and the period of coatings exposure during heating may vary depending on the desired condition of application. Thermal resistance of coating can also be determined relative to the change in adhesion strength of coating, but the most common approach is visual inspection of coating for cracking or delamination from the base.

The tests of sealing coatings for corrosion resistance are performed by immersing the specimens in a saturated saline solution in the furnace at a set temperature, which is higher than the room temperature and lower than 100 °C. The specimens are maintained in these conditions for several hours and then visual inspection for the presence of corrosion traces is carried out [9]. After tests in this case, the results are only qualitative, so it is difficult to compare the results of different tests.

CONCLUSIONS

1. Based on the analysis of literature data on operating conditions of GTE, it was established that one of the methods to increase the efficiency of engines is to create an effective system of sealing the flow path of compressor and turbine by thermal deposition of abradable coatings on the stator surface.

2. The basic requirements for the properties of sealing coatings, which include a tendency to abrasion and erosion resistance, were identified.

3. It was established that the main materials for deposition of sealing coatings on the casing of a compressor part of GTE, where temperature mode does not exceed 500 °C, are materials based on aluminum; for sections of compressor with an operating temperature of up to 800 °C — McrAlY-based materials (M = = Co, Ni or Co/Ni); for high-temperature sections of turbines ceramic materials based on zirconium oxide are used. As a dislocation phase in thermal sealing coatings, solid lubricants and polymers are used.

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CONFLICT OF INTEREST

The Authors declare no conflict of interest

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