Increasing wear resistance of the hinge guide compressor in aircraft engine

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Abstract. The article is devoted to the problem of increasing reliability and a service life of the cylindrical hinge for turning the blades of a guide axial compressor of aircraft engines under sliding friction without lubrication. The prospects of using nanostructured crystals of zirconium dioxide partially stabilized by yttrium oxide are justified. High anti-friction properties of the hinge are provided by the selection of the counterface material. Particular attention is paid to the resistance to scoring of the studied friction pairs. It has been established that the most promising counterfaces for the crystals of zirconium dioxide are molybdenum selenide coatings and alpha-titanium alloys.

1. Introduction
The subject of the study is the axial compressor steering apparatus, which serves to control the angle of entry of the air flow to the compressor blade. The highest compressor efficiency depends on the optimum angle. With a certain amount of flow deviation, surge may occur, which leads to catastrophic destruction of the compressor. The mounting of the vanes of the guide vane to the compressor casing, as a rule, is made in the form of a cylindrical hinge [1]. This hinge works in the severe conditions under current loads and high temperatures, reaching 600 °C. At such temperatures, the use of liquid lubricants is not possible. Solid lubricants have a short resource. Structurally, due to the small size of the hinge, it is not possible to locate the lubrication layer recovery systems. Therefore, the selection of a friction pair for the manufacture of a hinge that can operate without lubrication at high temperatures is a very urgent problem, which receives a lot of attention.

The study of the wear mechanism in cylindrical joints is an urgent problem. Good self-lubricating characteristics in humid air during dry sliding of an Al-Si alloy impregnated with graphite to (56 vol. %) are shown in the work [2]. Researches of the composite were carried out with bearing steel according to the disk-finger scheme. The effect of humidity on tribological characteristics is established. On the sliding surface of the disk due to particle smearing, wide compact films are formed consisting of graphite particles and metal wear particles. These films prevent the sliding of surfaces from contact of metal with metal. As applied to friction without lubrication, the studies carried out in [3] covered a wide range of different coatings in terms of hardness and chemical composition of various coatings obtained by vacuum deposition methods, modified anodized coatings (for aluminum), galvanic nickel – cobalt coatings, occlusion of pores of nickel coatings with fluoroplastic, coatings MoS₂. A lot of researches have been devoted to the study of the wear mechanism in cylindrical joints. The mechanisms of friction and wear during dry sliding of composites made of carbon nanoparticles reinforced with a nickel matrix
under conditions of elastic and elastic-plastic contact were studied in the work [4]. For this purpose, multi-walled carbon nanotubes and nanodiamonds, representing a wide variety of carbon nanoparticles, were chosen. The analysis of friction and wear is supported by the methods of physical research of surfaces, including scanning electron microscopy, transmission electron microscopy, Raman spectroscopy, light microscopy, and laser scanning microscopy. It has been established that carbon nanotubes provide effective contact lubrication. A study of the tribological properties of plain bearing bushings during dry friction without lubrication was considered in the work [5]. It was found that the coefficient of friction and wear rate first decrease and then increase, the optimal composition of the composite material used is determined. The frictional properties of a newly developed bearing made of a lead-free aluminum alloy with a low friction layer on its inner surface, which consists of a layer of molybdenum disulfide (MoS_2) deposited directly without any binders, such as resin are described in the work [6]. The frictional behavior of thin films of plastic materials mixed with molybdenum disulfide on steel substrates deposited by the layer-by-layer method was studied [7]. The features of friction of materials in air and dry nitrogen, as well as heat treatment of coatings for tribological characteristics, were studied. The effect of carbides in bearing steel of the M50 grade was studied depending on the degree of recovery during cold rolling. It was found that the coefficient of friction, as well as the wear rate, decreases with an increase in the decrease in cold rolling [8]. This result is explained by the formation of a stable self-lubricating film in the subsurface layer. Similar results were obtained in [9], where friction and wear of silicon carbide and carbon-graphite disks during dry sliding friction were studied using laboratory friction machines.

A systematic experimental study was performed in [10] to evaluate the tribological sliding properties of the highly entropic CoCrFeNiMo0 alloy. Detailed mechanisms of wear were investigated by studying the morphology of the worn surface, the chemical composition and microstructure of its cross section. The dominant wear mechanisms varied from abrasion and plastic deformation to oxidative wear and delamination with an increase in sliding time and normal load. It was established in [11] that the wear mechanisms of composites include both adhesion and delamination. Cr and Ag additives simultaneously increase the wear resistance and lubricity of the composites. Self-lubricating and high-strength composites have become a highly demanded material for cylindrical joints due to their significant potential in downsizing and weight saving [12].

In the experiments, the contact pressure between the sleeve and the shaft ranged from 20 MPa to 140 MPa, and the joint speed was from 10 deg/C to 60 deg/C. In [13], the wear mechanism was investigated using microscopic observations. An in-depth analysis of the chemical, physical, and tribological behavior of the infused epoxy matrix is carried out for applications aimed at reducing dry friction. Epoxy substrates were obtained by infusion of fullerene C70 and multi-walled carbon nanotubes in a mass concentration of 1, 3 and 5 wt.%. Thermal analysis showed a high glass transition temperature of carbon fillers compared to a pure epoxy substrate. The frictional and wear-resistant properties of the Al-25Zn-3Cu-3Si alloy were studied [14] in a wide range of pressures and sliding speeds on a friction machine according to a finger-disk scheme. The friction coefficient of the alloy increased with sliding speed, but decreased with increasing pressure to 1.5 MPa. However, the temperature and wear of the alloy continuously increased with increasing pressure and sliding speed. In [15], the results of studying the influence of normal load, sliding speed, and surface temperature on the behavior of dry sliding during wear of a friction-treated nickel-aluminum bronze alloy are presented. When creating friction units operating at high temperatures, structural ceramics and crystals are increasingly used. High hardness, heat resistance, corrosion and abrasion resistance, low density, as well as high fracture toughness of certain types of ceramics and crystals provide a diverse application of these materials in engineering. The combination of high mechanical strength, heat resistance and chemical inertness makes it promising to use refractory materials, such as ceramics and crystals, as structural and tribotechnical materials for friction units operating at high temperatures. In this case, crystals and ceramics used as friction elements must have a sufficiently high fracture toughness (crack resistance), as well as good antifriction properties. The most promising ceramic materials for working at high temperatures include materials based on zirconium oxides, because they have the highest crack resistance, especially the crystals of
zirconium dioxide [16]. The distribution of contact loads on the friction surfaces of a cylindrical hinge strongly depends on the size of the gap; therefore, it is advisable to study the tribological properties of the friction pair used in the hinge on model flat samples with reciprocating motion. The purpose of work is to investigate the tribological characteristics of the crystals of zirconium dioxide when operating without lubrication under the conditions of operation of the hinge for turning the vanes of the axial compressor guide vanes.

2. Materials and methods
The object of the study is friction pairs composed of nanostructured crystals of partially stabilized zirconium dioxide and a counterface made of materials promising for use in the hinge of the rotation unit of the compressor guide vanes. Counterface materials are the following: VT9 titanium alloy (alpha); chrome steel; zirconium ceramics; MoSe$_2$ antifriction coating; ion-plasma coating TiN.

The microhardness of the materials was determined on an MTI-3M instrument according to the procedure [17], and the indenter was a Vickers diamond tetrahedral pyramid.

The structures of the PSZ crystals were studied using a JEOL 5910 LV electron microscope.

To determine the antifriction properties, a plane-finger test scheme with reciprocating motion of the samples was selected. A plate measuring 80x20 mm is made from the material of the inner sleeve, and 10x10x4 mm of the outer plate sleeve from the PSZ crystal. The test procedure was developed based on the study of the operation of the cylindrical hinge. The performance and durability of the sliding bearings of the rotation unit of the vanes of the guide apparatus of the high-pressure compressor is determined mainly by the heat resistance and wear resistance of the rubbing elements. The main criteria for their performance can be expressed on the basis of temperature restrictions $[\Theta_1] \leq \Theta \leq [\Theta_2]$, acceptable contact stresses (pressures) $P \leq [P]$, wear intensities $I_h \leq [I_h]$, and moments of resistance to rotation (friction) $T_{\text{fr}} \leq [T_{\text{fr}}]$.

The sliding bearings of the rotation node of the blades of the high pressure compressor guide vane by design are cylindrical swivel joints, the service life of which is determined by the formula:

$$ T = \frac{[h]}{[(I_{h1}S_1 + I_{h2}S_2)\times n]} $$

(1)

where: $T$ is the service life of the sliding supports (durability); $[h]$ is the maximum allowable linear wear in the direction of the load; $I_{h1}, I_{h2}$ are average values of the wear intensities of the material of the sleeve and shaft in the conditions of operation of the connection; $S_1, S_2$ are the ways of friction of the shaft and the sleeve in one revolution or one cycle of movement of the movable element; $n$ is the rotation frequency or the number of cycles of movement of the movable element per unit time.

With reference to the sliding bearings of the rotation unit of the vanes of the guide vane, we transform the formula (1) to the form:

$$ T = \frac{[h]}{I_1 \sum_{i=1}^{n} \alpha_i R_i + 2I_2 \varphi_0 R_2 n} $$

(2)

where: $\alpha_i$ is an angle of rotation of the blades; $\varphi_0$ is a half of the arc of contact of the shaft with the sleeve (half of the angle of coverage); $n$ is the number of rotations of the blade per unit time (per hour); $\sum_{i=1}^{n} \alpha_i = \alpha \times n$, where $\alpha_{\text{avg}}$ is an average value of the angle of rotation.

To assess the temperature of the friction surfaces and the wear rate of the tribological elements, it is necessary to determine the contact parameters. The contact parameters of the cylindrical sliding bearings include: an arc of contact of the shaft with the sleeve, characterized by an angle of coverage of $2 \times \varphi_0$; contact pressure distribution $P(\varphi)$; maximum value of contact pressure $P_{\text{max}}$. The hinge diagram is shown in figure 1.
Figure 1. General view of the rotary cylindrical hinge of the blades: 1 - casing, 2 - axle of the blade, 3 - inner sleeve, 4 - outer sleeve, 5 - lever of the rotary ring.

The initial data for calculating the contact parameters of the sliding supports are structural characteristics of the supports (l, R₁, ε, γ=R₁/R₂); mechanical properties of the sleeve material (E₁,μ₁) and shaft (E₂, μ₂); current load (P).

Accepted designations are the following: l is a length of the contact of the shaft and the sleeve; R₁ is an inner radius of the sleeve; R₂ is a radius of the shaft (spike); ε = (R₁ - R₂) is a radial clearance of the interface; (E₁, μ₁), (E₂, μ₂) are the elastic modulus and Poisson’s ratio of the materials of the sleeve and shaft, respectively.

To calculate the contact parameters, you can use the solution of G. Hertz for the case of internal contact of the cylinders, if the condition is the following:

$$\alpha \times [(1-\mu_1^2) + (1-\mu_2^2)\psi] \leq 0.092,$$

where $$\alpha = \frac{P_0}{E_1\varepsilon}$$; $$\psi = \frac{E_1}{E_2}$$; $$P_0$$ is a load per unit length of the shaft-sleeve contact.

Conditions (3) for each friction pair are satisfied for the characteristic size of the nominal diameter of the cylindrical hinge at the minimum ($$\varepsilon_{\text{min}} = 0.02 \text{ mm}$$) and maximum ($$\varepsilon_{\text{max}} = 0.05 \text{ mm}$$) radial clearance of integration. The value of the maximum pressure in the center of the contact zone is determined by the formula:

$$P_{\text{max}} = \frac{2P_0}{\pi R_1 \sin \phi_0}$$

(4)

The average pressure at the contact $$P_{cp}$$ is determined by the formula:

$$P_{cp} = \frac{P_0}{2R_1\phi_0}$$

(5)

3. Results

The blades of aviation compressors are made of titanium alloys, and nickel alloys are used in bearings operating without lubrication at high temperatures [1], the antifriction properties of which are significantly inferior to zirconia-based ceramic materials. The calculation of contact parameters for the friction pair “VT9 titanium alloy - partially stabilized zirconium deoxide crystal” was performed at $$\varepsilon_{\text{min}} = 0.02 \text{ mm}$$ and $$\varepsilon_{\text{max}} = 0.05 \text{ mm}$$ depending on the radial load. The tribological characteristics of the friction pair depend on the load. Figure 2 shows the values of the contact parameters of the sliding bearings of the rotation node of the vanes of the guide apparatus, depending on the radial load P, calculated by formulas 4 and 5.
The stability of the tribological and strength properties of PSZ crystals is highly dependent on the amount of stabilizing additive of yttrium oxide. In the case of tribotechnical applications, the range of (0-4)% of \( \text{Y}_2\text{O}_3 \) additive is of practical interest, because in this interval the hardness and crack resistance of PSZ crystals are maximum. The metrological assurance of the accuracy of microhardness measurements is based on the statistical processing of the results (table 1).

**Table 1.** Statistical test data for the kinetic microhardness of PSZ crystals with different contents of the stabilizing additive \( \text{Y}_2\text{O}_3 \).

| Content \( \% \text{Y}_2\text{O}_3 \) | 0    | 2.5  | 3    | 4    |
|----------------------------------|------|------|------|------|
| Medium, HV                       | 319.6| 1032.3| 1137.0| 1080.0|
| Standard error of the mean, \( \mu \) | 50.8 | 77.8 | 95.8 | 8.0  |
| Median, \( Me \)                 | 279.4| 956.5| 1071.4| 1071.4|
| Mode, \( Mo \)                   | 233.6| 1187.1| 846.5 | 1071.4|
| Standard deviate, \( s \)        | 152.4| 258.0| 317.8| 26.6 |
| Sampling variance, \( s^2 \)     | 23218.3| 66578.5| 100980.2| 705.9|
| Kurtosis, \( \varepsilon_k \)    | -1.291| -1.426| -1.727| -0.421|
| Asymmetric property, \( A_s \)   | 0.420| -0.057| 0.177| 0.163|
| Interval, \( \Delta \)           | 422.8| 747.2| 860.2| 90.5 |
| Minimum                          | 130.4| 625.9| 714.0| 1036.5|
| Maximum                          | 533.2| 1373.1| 1574.1| 1127.0|
| Sum, \( \Sigma \)                | 2876.8| 11354.8| 12506.6| 11888.9|
| Level of reliability (95%), \( \frac{HV}{1.645\times\mu} \) | 120.1| 173.3| 226.6| 18.9 |
| Number of diagrams, \( n \)      | 11   | 11   | 11   | 11   |
| Elasticity, \( K_e \)            | 0.355| 0.521| 0.601| 0.622|
| Plasticity, \( K_p \)            | 0.645| 0.479| 0.399| 0.378|

Transmission electron microscopy showed the presence of colonies in the structure of \( \text{ZrO}_2\)-3mol\% \( \text{Y}_2\text{O}_3 \) crystals with sizes ranging from 30 to 100 nm wide and \( \sim 400 \) nm in length [16].

The best tribological characteristics of a hinge with a sleeve made of PSZ crystal can be achieved by selecting a counterface. As applied to the cylindrical hinge of fastening the blades of the guide apparatus of axial compressors, bench tests were carried out (table 2), simulating the averaged load-speed
An analysis of the friction surface of a reference sample of ZrO₂ + 3.5 mol% Y₂O₃ crystals on steel (figure 3) shows that the following surfaces are present on the friction surface of the investigated crystal:

- films of secondary structures covering the surface of the matrix material;
- wear products of varying degrees of compaction located on a matrix basis in the gaps between the individual sections of the film;
- individual small areas of the surface of the matrix material without film.

In the films of secondary structures, individual hairy cracks are noted, which, as a rule, are localized within the film without spreading to the matrix base. Along with zirconium and yttrium, both the film and the wear products contain iron transferred in the process of contact interaction with the surface of the steel counterface. However, the content of these elements in different parts of the surface is different. For example, an analysis of 8 points on the surface showed that the amount of iron ranges from 3.71-60.51%, the amount of zirconium varies from 15.28 to 64.69%, the amount of yttrium from 0.76 to 4.5% (table 3).
Table 3. The distribution of elements along the friction surface of a sample of crystals.

| Spectrum        | Content of elements in atom% |
|-----------------|------------------------------|
|                 | B   | Al  | Fe  | Y   | Zr  | Hf  | O   | Total |
| Sum Spectrum    | yes | 0.09| 32.6| 2.4 | 39.6| 0.9 | 24.1| 100   |
| Spectrum 2      | yes | 0.10| 46.5| 1.4 | 27.9| 0.6 | 23.5| 100   |
| Spectrum 3      | yes | 0.00| 60.5| 0.7 | 15.2| 0.4 | 22.9| 100   |
| Spectrum 4      | yes | 0.04| 29.8| 2.6 | 42.4| 0.7 | 24.2| 100   |
| Spectrum 5      | yes | 0.08| 18.4| 3.7 | 51.2| 1.7 | 24.6| 100   |
| Spectrum 6      | yes | 0.16| 14.6| 3.9 | 54.9| 1.3 | 24.9| 100   |
| Spectrum 7      | yes | 0.07| 14.5| 3.1 | 56.1| 1.2 | 24.9| 100   |
| Spectrum 8      | yes | 0.04| 3.71| 4.5 | 64.6| 1.7 | 25.3| 100   |
| Average         | -   | 0.04| 27.6| 2.8 | 44.0| 1.1 | 24.3| -     |
| Standart deviation | -  | 0.08| 18.7| 1.2 | 16.2| 0.4 | 0.78| -     |
| Max.            | -   | 0.16| 60.5| 4.5 | 64.6| 1.7 | 25.3| -     |
| Min.            | -   | 0.10| 3.71| 0.7 | 15.2| 0.4 | 22.9| -     |

According to the results of electron microscopic analysis of surface fracture-wear of the investigated samples, it was established that this wear process includes several stages:

- Formation of primary wear products partially accumulated in the friction zone;
- Friction transfer of the counterface material to the friction surface of PSZ samples;
- Formation of films of secondary structures on the friction surface of PSZ crystals due to compaction of wear products transferred from the friction surface of the counterface of the material, as well as due to the development of oxidation processes, possible phase transformations, etc.;
- The occurrence of microcracks, peeling and destruction of the surface layer with the formation of secondary wear products.

The stability of the wear process and the spread of experimental wear data are significantly affected by the ratio of the rates of formation, accumulation of fatigue damage and, accordingly, the destruction of surface films. These processes ultimately determine the possibility of localization of fracture (crack) in the film or the propagation of fracture in the underlying layers of the matrix material.

4. Conclusion
Nanostructured crystals of partially stabilized zirconium dioxide satisfy the working conditions of the sliding bearings of the rotor blades of the guide vanes of the axial high-pressure compressor according to the temperature and strength criteria, as well as the wear resistance criterion. It has been experimentally established that a friction pair composed of a nanostructured PSZ crystal and a MoSe$_2$ coating have better tribological properties. The use of PSZ nanostructured crystal for the manufacture of sliding bearing bushings from will increase the service life of the blade rotation unit by more than 2–3 times.

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