Antifriction properties of ceramic materials under high-speed sliding process

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Abstract. The issues of tribology of a composite cermet material under high-speed short-term dry sliding friction process are discussed in this article. The possibility of reducing the friction coefficient due to the processing of cermet with selenium vapor is substantiated. Model experiments were carried out on a laboratory friction machine according to the pin-on-disk test at sliding speeds up to 100 m/s. Experimental dependences of the coefficient of friction on speed, load and the effect of mechanical properties on friction and wear of a friction couple are analyzed. These studies were based on the assumption about the possibility of reducing the friction coefficient of cermet by processing in chalcogen vapor and restoring the antifriction properties of the resulting lubricating film with an increase in temperature from friction heating of friction surfaces. It is proposed to carry out processing in chalcogen vapors of thermal protection ceramic coatings of the housings of the axial machines gas path, in particular, in aircraft engines. This technological process in conditions of emergency contact of the housing with the blades of the rapidly rotating disk will reduce the risk of engine destruction with catastrophic consequences.

1. Introduction
The thermoimpulse friction is possible under conditions of high-speed dry sliding friction when the blades of the rapidly rotating disk touch the housing of an axial machine gas path. The consequences of such a touch can lead to an accident, and in the case of aircraft engines, to a catastrophe. It is extremely difficult to avoid contact of the disc with the housing, because a clearance increase of the disc and the housing leads to gas leakage and a decrease in the efficiency of the engine. The surface of the housing is covered with thermal protection plasma gas-thermal coatings of powdered refractory materials, most often containing partially stabilized zirconium dioxide. The joints of refractory materials are very hard, therefore, technological provision of dimensional accuracy in the process of manufacturing parts is very tough and expensive. To improve the probability of survival, it is necessary to reduce the coefficient of friction; therefore, much attention is paid to the issue of improving antifriction properties in the disc-housing coupling. To improve the performance and reliability of the engine, real-time simulation is used [1]. The influence of the clearance and wall friction on the energy of the gas flow and the efficiency of the seal was studied by the method of modeling [2]. The influence of wear of parts on the performance of the turbine is shown. A detailed analysis [3] of the destruction of the turbine wheel of an aircraft engine has been carried out, as a result of which damage leading to destruction has been established. Sliding friction up to a speed of 300 m/s was studied under process of the titanium blade contact with the housing [4]. The antifriction properties of the friction surface are improved by using [5] solid
lubricants. The efficiency of using tungsten and molybdenum chalcogenides applied by vapor deposition is shown. In the process of surface friction at high speeds on the frictional contact, a local increase in temperature occurs, leading to the destruction of the coating. Calculation models of friction and wear of high-speed friction units include temperature effects [6]. To reduce the friction coefficient, [7] self-lubricating composite coatings are used. Much attention is paid [8] to self-lubricating composite coatings with a ceramic matrix and a metal matrix. The works [9, 10] are devoted to the choice of the ceramic phase. The importance of the choice of the microstructure of coatings [11, 12] and mechanical properties [13, 14] is noted. The work [15] is devoted to the study of wear resistance of a composite coating with a metal matrix, in which it is shown that cermet based on Co-TiCN, applied to the friction surface by arc ion sputtering, has a very high adhesive bond strength. In [16], it is noted that in such coatings, as a result of wear, microcracks are observed on the friction surfaces. In terms of wear resistance, it is promising to use TiC-based cermets with a TiC-Ni3Al binder. In [17], the mechanism of dry friction wear was investigated for cermet based on Mo2FeB2. It was found that the adding of Mn and Cr increases the wear resistance of the surfaces. When solid lubricants (graphite, MoS2 and Ag) are added to the cermet composition, the effect of self-lubrication of the friction surface appears [18]; however, during operation, the lubricating layer of the solid lubricant is destroyed, therefore, it must be restored. In [19], it was proposed to introduce chalcogen vapors into contact. The behavior of such a self-lubricating material under high-speed friction has been little studied.

The aim of this work is to investigate the antifriction properties of a cermet coating treated in selenium vapor under high-speed (up to 100 m/s) friction without lubrication on steel.

2. Materials
The tests were carried out on a composite with a metal matrix based on iron. Composition of the composite according to spectral analysis data: C - 19.46, Si - 3.92, P - 1.41, Mn - 0.47, Cu - 0.55, Fe - the rest. Samples were tested in the initial state and after treatment in selenium vapor. A composite with a ceramic matrix based on zirconium dioxide of the composition ZrO2 + 3 mol% Y2O3, obtained from nanopowders synthesized by sol-gel processing, samples of which were prepared using ceramic technology with slip casting, was chosen as a reference standard.

3. Equipment
The tests were carried out on a UMT machine according to the pin-on-disk test, in which a steel disk with a diameter of 320 mm is installed, a pin with a square section of 5 mm. The number of revolutions of the disk was brought to 6000 rpm by modernizing the drive of the testing machine. The wear of the samples was determined by the gravimetric method on an electronic balance Shinko Vibra HTR-220 CE (Japan) with subsequent recalculation for linear wear. The mechanical properties were monitored using a kinetic microhardness tester based on a compact platform CSM-instruments M H T-Z-AE (Switzerland). The positioning accuracy of the instrument is 0.1 μm. The technology for modifying cermet was implemented on a bench for processing materials with selenium and tellurium vapors [20].

4. Results
Analysis of the structure of the cermet sample showed that the material is porous at higher magnification (figure 1), the boundaries between the powder particles are visible. The material is made using ceramic technology from powders, the fineness of which is less than 10 microns.
The mechanical properties of all samples were determined by kinetic microindentation. The microhardness values were estimated as an average value of ~ ten measurements, while the minimum and maximum values of the indentation diagonal were excluded as random variables. These random variables are caused by the inhomogeneity of the structure of the samples, due to the modes of technology and don't depend on the method of processing the results of measurements of the diagonals of the indentation. The measurement results showed that samples of materials based on PSZ have the highest microhardness, the values of which are practically independent of the composition and, on average, vary in the range of $H_{\text{vav}} = 16.2 \pm 0.4$ GPa. Table 1 shows the test results.

| Material                        | Specific gravity (g cm$^{-3}$) | E, GPa | $H_{\text{v}}$ |
|--------------------------------|-------------------------------|--------|---------------|
| Zirconium ceramics             | 5.8                           | 214    | 1620          |
| Cermet as delivered            | 6.0                           | 172    | 480           |
| Cermet after processing in selenium vapor | -                             | 157    | 16            |

Before carrying out tribological tests, the samples were washed in gasoline. In accordance with the accepted experimental procedure, the disk sample was brought to a given speed mode and a normal load was applied. The calculated dependences for determining the average contact pressure $p$ (N/m$^2$), sliding speed $v$ (m/s), sliding friction coefficient $f$ will have the following form:

$$p = 4 \frac{N_1}{\pi d^2}, \quad v = \frac{\pi \rho n}{30}, \quad f = \frac{M_1}{\rho N_1},$$

where $N_1$ is the load per pin sample; $d$ is the diameter of the pin sample; $\rho$ is the distance from the axis of rotation of the disk sample 7 to the axis of the pin sample 6; $n$ is the number of revolutions of the disk sample; $M_1$ is the frictional moment per sample.

Figure 2 shows the effect of the sliding speed of a cermet sample as delivered.
The analysis of the friction surfaces after the completion of the tests shows that in the range of speed 0-60 m/s, the decrease in the friction coefficient with increasing speed can be explained by the softening of the material due to frictional heating, in the range of speed from 60 and more m/s. The increase in the friction coefficient that occurs due to the transfer (coating) with particles of the counter face material to the friction surface. Figure 3 shows the effect of contact pressure on the friction coefficient of cermet in the initial state at a sliding speed of 70 m/s.

The form of the curve of the dependence of the friction coefficient is fully described by the concepts of the molecular-mechanical theory of friction. Figure 4 shows the results of determining the friction coefficient under high-speed tribotechnical tests at a sliding speed of 97.4 m/s and a load of 0.68 MPa. The experiments were carried out with promising materials for a high-speed friction unit, namely: zirconium ceramics, metal-ceramic composite with a matrix based on iron in the initial state, and processed in selenium vapor. The main criterion for the selection of material was the coefficient of friction.
Experiments have shown that selenizing is a highly efficient technological operation, which made it possible to reduce the friction coefficient by almost three times in comparison with zirconium ceramics. To assess the resistance of the modified friction surface to fracture under short-term thermoimpulse friction, we will choose a dimensionless wear resistance index \( G \) under GOST 23.001-2004

\[ G = \frac{L}{h}, \]

where \( L \) is the interval of the friction path; \( h \) - linear wear increment.

The wear resistance index is determined \((G)\) in the same dimensions of the values of the friction path and linear wear of the surface, therefore the \( G \) index is numerically very large and for ease of use is displayed as \( \log G \). Figure 5 shows the dependence of the wear resistance index on pressure.

5. Discussion

It was found experimentally that \( \log G \) varies almost linearly with increasing. Consequently, the wear resistance of the friction surface with increasing contact pressure is described by a nonlinear graph of the exponential function and with a negative exponent, i.e. descending branch. The physical principles of creating a new generation of self-lubricating composites with a ceramic matrix for operation at high
temperatures are based on the Vasiliev-Savage hypothesis that friction of solid lubricants creates a lubricating layer of adsorbed molecules at the points of actual contact. Ceramic material can be antifrictional at high temperatures if it contains a filler that, when heated, emits chalcogen vapor, which reacts with the solid lubricating coating material to restore the antifriction properties of the contacting friction couple. At the moment the disc touches the housing, a sharp local increase in temperature occurs, at which decomposition of iron selenide occurs, chalcogen (selenium) vapors are formed, which in the zones of actual contact react with the material of the surface layers, in particular the solid lubricating coating, and restore its lubricating ability. The coefficient of friction decreases significantly.

6. Summary
The high-speed tribological tests carried out have shown the efficiency of processing cermet in chalcogen vapors; it has been established that, under short-term thermoimpulse friction on modified contact surfaces, a decrease in the friction coefficient is observed. It is recommended to carry out the treatment in chalcogen vapors of thermal protection ceramic coatings of the housings of the gas path of axial machines. This technological process under emergency contact of the housing with rapidly rotating disk blades will reduce the risk of engine destruction with catastrophic consequences.

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