Improvement of antifriction properties of sliding bearings with ceramic sleeves made of zirconium dioxide

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Abstract. The article is devoted to the investigation of the tribological properties of a sliding bearing with a ceramic sleeve made of zirconium dioxide powder stabilized with yttrium oxide. The paper studies antifriction properties of a bearing under friction without lubrication in the range of contact pressure of 0.05 - 0.5 MPa at the speed of 0.5 - 3 m/s in relation to the operating conditions of the support of a submersible centrifugal pump for oil production. The possibilities of improving the antifriction bearing’s properties by processing a ceramic sleeve in selenium vapor are analyzed. The assumption about the prospects of using ceramic sleeves with a modified friction surface in the chemical and oil-gas industry is justified.

1. Introduction
In the chemical and oil and gas industry, the requirements for corrosion resistance are imposed on the material of the friction machines’ units, especially at high temperatures. The interest in ceramic materials based on partially stabilized zirconium is due to a unique combination of strength properties, crack resistance, and chemical stability. However, it is not possible to lubricate a bearing, in conditions of dry friction, a dangerous situation arises and a bearing unit may be destroyed, for example, at high temperature or irregularities in the lubrication system of the friction unit. Therefore, it is necessary to generate a surface layer with a low shear resistance on the friction surface of the ceramic sleeve. The service life of antifriction coatings is very limited. It is necessary to resurface coating for a prolong operation. In addition, the adhesion of antifriction coatings to the surface of zirconium-based ceramics is characterized by small shear strength parameters. The obtained materials based on zirconium dioxide are multiphase solid solutions of zirconium oxide with one or more oxides of alkaline earth and rare earth elements. As a rule, such materials are metastable at room temperature, but nevertheless, they can have a fairly high degree of stability and they do not undergo phase transformations for a long time under repeated temperature influences and under certain conditions. The stability degree of ZrO₂-based materials, as well as their phase composition, structure, and physicochemical properties, depend on the type and concentration of the stabilizing oxide, the presence of additional impurities, the synthesis method, and the mode of subsequent heat treatment. When synthesized from a melt, a growing partially stabilized zirconium dioxide (PSZ) single crystal has an initial cubic structure, and phase transformations occur in it during cooling in the solid phase. The transformation of the cubic phase to the tetragonal phase is accompanied by the formation of a domain structure in crystals. Nowadays, the method of directional crystallization of the melt in a “cold” container using direct high-frequency heating is the only high-performance method that allows
obtaining bulk single-crystal materials based on zirconium dioxide to ensure systemic investigation and practical use.

The synthesis technology of ceramic materials is developing in the direction of the technology of formation and sintering, as well as the use of nanostructured powders. In [4], ceramics were produced by the method of spark plasma sintering. As a result, the ZrO2 grain size decreased from 250 Nm to 160 Nm and nano-SiC nanoparticles were added. The obtained fine-grained structure and the film formed on the surface improved the antiwear properties of ceramics. In [5], a ceramic composite based on zirconium dioxide was fabricated by laser surface surfacing. Tribological tests under dry friction conditions showed that the addition of ZrO2 reduced the coefficient of friction, and the synthesized composite showed good tribological properties. Carbon nanotubes are added to the coating to improve the tribological properties of the composites [6]. In practice, disperse composites strengthening the system of alumina and tetragonal zirconium dioxide stabilized by cerium cation is widely used [7]. The tribological properties of zirconium dioxide-based ceramic composites are strongly affected by the amount of stabilizing additive Y2O3 [8]. To improve the tribological properties of ceramic materials, the formation of a layered structure of the surface layer is used [9]. Tribological tests were carried out under continuous heating. Tribochemical reactions play a significant role in the implementation of continuous lubrication. The effect of enhancing tribological characteristics in a wide temperature range from 25 to 800° C is noted. The temperature factor in tribology is very important role in the synthesis [10] of ceramic parts and in the operation of the friction unit [11]. The tribological properties of zirconium ceramics depend on the surface roughness [12, 13], load, and speed [14]. The homogeneity of the ceramic material is important as well, i.e., a size of the powder particles and its distribution over the volume of the ceramic sample [15, 16]. In [17], a correlation was established between the tribological properties and the phase structure of the ceramic composite. A great attention is paid to experimental investigations of the tribological properties of zirconium ceramics in the friction units of machines and devices [18-20]. The aim of the article is to conduct comparative tests to determine the antifriction properties of sliding bearings with ceramic bushings made of zirconium dioxide under friction without lubrication.

2. Materials, test procedures and samples
The object of the test was bearings with ceramic sleeves made of nanostructured zirconium dioxide powders stabilized with 2.8% Y2O3 (a composite with a ceramic matrix) and sleeves whose friction surface was modified in selenium vapor.

The purpose of this operation is to develop a chalcogenide in ceramics, which decomposes with increasing temperature to form a chalcogen. It reacts with the counter body and forms a protective film on the friction surface [12]. An increase in surface temperature in local contact, as a rule, occurs during friction before scoring and surface failure. The steel X18H10T was chosen as a counter body.

The mechanical properties of the surface layer were determined from the indentation diagram of the Vickers diamond pyramid on a CSM kinetic microhardness tester (microindentation system based on the compact platform CSM-instruments MHT - Z - AE - 000). The methodology for estimation the material plasticity was in accordance with the International Standard “Metallic Materials - Instrumented Indentation Test for Hardness and Materials Parameters” ISO / DIS 14577.

Tribotechnical tests were conducted out on the II 5018 friction and wear material testing machine. The wear was determined by the weighing method on Shinko Vibra HTR-220 CE electronic laboratory analytical balance, the measurement accuracy was 0.5 mg.

3. The results of the experiment and discussion
The efficiency of the material in the friction unit depends on the properties of the surface layer. Almost the only method for estimating the mechanical characteristics of the surface layer of the material is the kinetic indentation method. The results obtained at a load of 3 N guaranteed to cover the thickness of the layer involved in the friction process are important for the analysis of the bearing operability in the set friction parameters. Sleeves were produced using casting technology followed by
sintering at \( t = 1400 \, ^\circ \text{C} \). The micro hardness of the materials the sleeves were made of was estimated from the average of 10 measurements of the imprint diameter.

The microhardness values of six sleeves made by a single technology (casting at 1400 \( ^\circ \text{C} \)) are significantly different. The average value of \( H_v \) is 10.83 \( \pm 2.3 \) GPa. The materials plasticity to a large extent determines their crack resistance. The higher the ductility, the higher the coefficient of crack resistance (\( K_{\text{IC}} \)). During the experiment, \( W_{\text{plast}} \) is determined. It is an irreversible loss of energy during indentation, equal to the area of the hysteresis loop in the indenter indentation diagram, i.e. the energy absorbed in the cycle “loading - unloading”. Also \( W \), mechanical operation of indentation, equal to the sum of elastic and plastic energy is estimated. The given paper determines the coefficient of irreversible energy loss during indentation (\( K_c \)), which is often called the plasticity coefficient. The term irreversible energy loss reflects the essence of the process more accurately, because irreversible energy loss also includes energy loss due to cracking. This coefficient is determined by the ratio:

\[
K_c = \frac{W_{\text{plast}}}{W}
\]

Figure 1 shows a diagram of the indentation of a Vickers microindenter into a ceramic composite with a zirconium dioxide matrix.

![Figure 1](image1.png)

**Figure 1.** Diagram of the Vickers microindenter indentation into the surface of the sleeve.

\( W_{\text{plast}} \) is estimated experimentally. The irreversible energy loss during indentation is equal to the area of the hysteresis loop in the indenter indentation diagram, i.e. the energy absorbed in the loading – unloading cycle and the \( W \), mechanical indentation operation is equal to the sum of the elastic and plastic energy. Given paper estimates the coefficient of irreversible energy loss during indentation (\( W_{\text{plast}} \)) which is often called the plasticity coefficient. The term irreversible energy loss more accurately reflects the essence of the process, because irreversible energy loss also includes energy loss due to cracking. This coefficient is determined by the ratio:

\[
K_c = \frac{W_{\text{plast}}}{W}
\]

Figure 2 shows a diagram of the kinetic microindentation of the processed sleeve.
Figure 2. Diagram of the Vickers microindenter indentation into the surface of the sleeve after treatment in selenium vapour.

Table 1 presents characteristics of the mechanical friction surfaces properties of ceramic sleeves in the initial state and after treatment with selenium vapor, obtained by the method of kinetic microindentation.

Table 1. Characteristics of the mechanical properties of ceramic sleeves (sleeve No. 1).

| bearing sleeve     | E, GPa | HV, Vickers | $H_{\text{max}}$, mkm | $W_{\text{упр}}$ | $W_{p}$ |
|--------------------|--------|-------------|----------------------|-----------------|--------|
| basic              | 87.4   | 8.5         | 5.13                 | 2.78            | 3.17   |
| selenation         | 11.5   | 27.7        | 22.2                 | 10.8            | 8.63   |

The sample testing was carried out according to the shaft-sleeve scheme. A 40X13 stainless steel specimen was mounted on the spindle shaft; its rotation was carried out from the electric motor of the machine (Figure 3). A sleeve made of a testing ceramic material was installed in the holder (in Figure 3 it is hidden by a fixing nut). A load was applied to the holder using a lever, which produces a radial force $P$. The operation principle of the machine is the abrasion of two samples pressed against each other by the force $P$. In the process of operation on the lower sample, the friction moment is measured. The temperature was measured on the shaft and the sleeve by the non-contact method with a MPro pyrometer from “Optris GmbH” in the process of testing. The procedure for presenting tribological testing data (in quantity and form) is formulated in accordance with the requirements of the standard manual for measuring and recording the friction coefficient (ASTM-6-115-98). The load and speed parameters of the tests were guided by the operating conditions of the bearing systems of submersible pumps when operating in the "dry" friction mode. The normal operating conditions of the sleeve mean the operating environment, i.e., formation fluid, temperature up to 250 °C. The maximum water content in the formation fluid is 99%. Comparative tribological tests of samples of sleeves with anti-friction coating and without coating have been carried out. The sleeves are tested in the lubrication mode with water, dry friction and after treatment with selenium vapor at speeds up to 2000 rpm and a load of up to 300 N. The main parameter of the bearing operation is a friction moment in the bearing pair.
Figure 3. Node friction machine II-5018 with installed samples.

Figure 4 shows the dependence of the friction moment in the bearing on the load. The loading was carried out stepwise.

![Graph showing the dependence of friction moment on load]

**Figure 4.** The dependence of the friction moment on the load during friction on steel: 1 - sleeves of PSZ-X18N10T lubricated with water, 2 - bushings of ChSTs-X18N10T at friction to dry, 3 - sleeves of PSZ with coating X18H10T at friction to dry.

It was revealed experimentally that the antifriction of the bearing in lubrication with water and friction without lubrication are close. Processing a ceramic sleeve in selenium vapor is able to reduce the friction moment in the bearing significantly and to increase the stability of the friction moment. The effect of rotation speed at the friction moment in the bearing is shown in figure 5.
Figure 5. Dependence of the friction moment on speed at a load of 0.141MPa at friction on steel: 1 - sleeve made of ceramic PSZ, lubricated with water; 2 - PSZ sleeve treated in selenium vapour.

The sleeves processed in selenium vapor up to the speed of 1.5 m/s have an almost constant friction moment with an increase in the shaft rotation speed. With a further increase in the sliding velocity, the friction moment is increasing. It can be explained by an increase in temperature. With increasing temperature, the hardness of the material decreases, and the molecular interaction at the contact has a dispersive nature, i.e. electrical. It is independent on temperature. Therefore, the friction coefficient and, accordingly, the friction moment should increase. When the bearing is lubricated with water at a speed of more than 1.5 m/s, a friction moment decreases. Due to the large friction losses, there is a strong heating of the surface and there is a significant increase in wear of both the sleeve and the shaft. This can be explained by the transition from normal sliding, when the steel counter body flows around the roughness of the ceramic sleeve, to the state when the micro-cutting process starts. With a continued increase in temperature, this condition leads to hardening of the sleeve.

4. Conclusion
The investigation of the tribotechnical characteristics of bearing sleeves, depending on the manufacturing technology, indicates that composite materials based on zirconium dioxide are not antifriction materials. The studied information can be used for the manufacture of bearing sleeves for operation in dry friction conditions only if there is an antifriction coating or a modified surface layer with low shear resistance. The experiments showed that according to the criterion of friction in the bearing, the treatment of zirconium sleeves in selenium vapor is able to improve the antifriction properties of a sliding bearing with a sleeve made of zirconia-based ceramic in two times.

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