Predicting the reliability of friction type bearings with zirconium ceramic bushing

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Abstract. The paper considers the issues of assessing the reliability of friction type bearing when installing a zirconium ceramic bushing. The allegations regarding the possibility of calculating the reliability of a bearing based on the results of friction pair wear tests at a laboratory setup were made. On a universal friction machine, the tribological characteristics of a friction pair are investigated using a disk-finger scheme. The methodology of constructing the elemental wear law is substantiated, according to which the wear intensity of the ceramic bearing bushing is adjusted according to the conditions of its operation. Particular attention is paid to the reliability of the obtained laboratory tests for friction and wear. Only parametric bearing failure based on the accumulation of wear damage is considered. A procedure has been developed for calculating the reliability and service life of a friction type bearing, taking into account the real angle of contact zone contact, variation of the sizes and tolerances of the shaft and bearing bushing, the normal distribution of errors, as well as the load and sliding velocity in the bearing.

1. Introduction
In machines of the agricultural sector of the economy, friction type bearings, on the one hand, are most often used because they are simple in design and manufacturability, and on the other hand, friction units in machines are mainly the cause of the loss of function. Agricultural machinery operates in dusty environments and in order to reduce the impact of abrasive on bearings, there is a tendency to use materials and hardening treatments to ensure maximum hardness of the friction surfaces. This fact makes the use of ceramic materials in friction units highly relevant. The interest in ceramic materials based on zirconium oxide is due to the practically highest crack resistance of this ceramic in comparison with other ceramic materials [1, 2]. The mechanical characteristics of ceramics are highly dependent on manufacturing technology. Tribological properties depend on the external conditions of friction, the state of rubbing surfaces, load, speed, temperature, and other factors [3, 4, 5]. Research is being conducted in the field of developing new technologies and studying the mechanical properties of ceramics [6].

The effect of the ceramic matrix composites on friction was studied [7]. In [8, 9], a high efficiency of adding alumina powder to a zirconium oxide matrix was established. Much attention in the technology of synthesis of zirconium ceramics is paid to the influence of the particle size of the powder on the mechanical characteristics of the obtained ceramic material [10, 11]. The usefulness of plasma surface treatment for strength and tribological properties of ceramics with a matrix based on zirconium and aluminum oxides with the addition of silicon carbide particles was considered in [12]. To improve
tribological properties and create the effect of self-lubrication during dry friction, carbon nanotubes are included in the ceramic composition [13]. The sol-gel technology has been widely used for the synthesis of nanostructured powders ZrO$_2$ from which ceramic composites with a zirconium matrix are made [14]. To improve the structure of zirconium ceramics, heat treatment is used [15]. Systematic studies of the strength properties of ceramic composites based on zirconium oxide were performed [16]. Currently, there are no recommendations on the design and manufacture of friction type bearings operating in the conditions of boundary and dry friction [17].

The wear of tribo-conjugates under the conditions of boundary and dry friction mainly determines the resource and reliability of the vast majority of machines, equipment, and mechanisms. The massive use of materials based on zirconium dioxide can raise the machine reliability to a new level. However, there is practically no systematic approach to the design of bearing bushings, which requires the development of guidance materials for the design and manufacture of bearing bushings. However, the current state of the science of machine reliability [18] enables to propose a methodology for assessing the resource and reliability of friction units at the machine design stage.

The purpose of the current work is to develop a methodology for calculating the life and reliability of friction type bearings with zirconium ceramic bushing operating in the conditions of boundary lubrication or dry friction.

2. Materials and equipment
Samples for tribotechnical tests are made of sintered material of the composition ZrO$_2$-3 mol. % Y$_2$O$_3$ from powders obtained by chemical deposition from salt solutions. The samples are made in the form of short rods (fingers) with a square section of 5x5 mm and a length of 10 mm. The end working surfaces of finger samples are flat with a roughness of Ra = 0.8. The counterbody in the form of a disk with a diameter of 120 mm is made of hardened tool steel U10A, HRC 49-52.

Friction and wear tests were carried out on a UMT-1 friction machine [19] according to the disk-to-finger scheme.

3. Results and discussion
The loss of performance of a friction type bearing due to wear is related to parametric failures. Gradual (parametric) failures depend on many factors, namely physical and mechanical properties, surface roughness, operating conditions - loads, speeds, temperature conditions, etc., which can change randomly during the operation of the product. The action of these factors leads to various laws of distribution of service life to failure. The most common is the normal distribution (Gaussian distribution). This is a symmetric distribution, the shape of which is determined by independent parameters: the mathematical expectation $\bar{t}$ and the standard deviation of a given random variable $\sigma$.

The probability density of the normal distribution:

$$f(t) = \frac{1}{\sigma(2\pi)^{1/2}} \exp\left[-\frac{(t-\bar{t})^2}{2\sigma^2}\right]$$

Reliability function:

$$P(t) = \frac{1}{\sigma(2\pi)^{1/2}} \int_{\bar{t}}^{\infty} \exp\left[-\frac{(t-\bar{t})^2}{2\sigma^2}\right] \, dt$$  \hspace{1cm} (1)

In practical work, to solve equation (1), use the tabulated normal distribution function (Laplace function) [18] by means of the quantiles of the normal distribution:

$$U_p = \frac{m - \bar{m}}{\sigma}$$
The failure rate in the case of a normal distribution is a variable that increases rapidly with increasing operating time; therefore, when determining the reliability indicator for parametric failures are not used. With regard to the assessment of the parameter of the parametric reliability of the mechanical system due to the wear of the element, the mathematical expectation of the parameter and its standard deviation are calculated by an independent method. From design considerations, according to experimental data or reference literature, the maximum permissible dimensions of the part are established until the time of rejection and decommissioning of the part $\Delta h_{PRED}$ the calculated value $\Delta h$ must be less than $h_{PRED}$. To ensure the probability of $P$ must be:

$$\Delta h - \Delta h_{PRED} = U_{p}S$$

$S$ – the standard deviation. Here it is assumed that the difference $h - h_{PRED}$ is distributed according to the normal law.

The probability of failure-free operation is determined by the quantile of the distribution:

$$U_{p} = -\frac{\bar{\Delta h}_{PRED} - \bar{\Delta h}}{(S_{PRED}^{2} - \bar{S}_{j}^{2})^{1/2}}$$

(2)

Typically, the calculation is based on a specified safety factor – $n$

$$\Delta \bar{h} \leq \frac{\Delta \bar{h}_{PRED}}{n}.$$  

Consider the relationship between $U_{p}$ and the safety factor $n$, calculated from the average values. Divide into $\Delta \bar{h}$:

$$U_{p} = -\frac{\bar{\Delta h}_{PRED} - 1}{\Delta h} = -\frac{\bar{n} - 1}{\left(S_{PRED}^{2} - \bar{S}_{j}^{2}\right)^{1/2}} = -\left(n^{2}\cdot v_{PRED}^{2} + \bar{v}_{j}^{2}\right)^{1/2},$$

where $\frac{S}{\Delta h} = \nu$ - the coefficient of variation.

If the limit values are normalized (for example, size tolerances), then it is considered that the tolerance field is covered by the interval 6$S$. According to the quantile of the distribution using the tables [18], the probability of failure-free operation is determined.

The calculation of the reliability of a friction type bearing is reduced to a comparison of the calculated wear characteristics of ceramic materials based on zirconium dioxide. For each point of the contact surface of the conjugated bodies, the process of wear of materials can be represented as a dimensionless quantity of wear rate of material J:

$$J = \frac{dh}{dl} = \frac{dh}{\nu \cdot dt}$$

(3)

where $h$ – the value of the worn material layer on the friction path $l$, $\nu$ – the relative sliding velocity of the conjugated bodies, $t$ – time.

Solving equation (3) with respect to $t$ and taking into account that when the total wear of the conjugated bodies $h$ reaches the maximum permissible value $[h]$, time $t$ takes on the meaning of the work resource $T$, we obtain:
where \( p \) – contact pressure.

The accuracy of the calculations is determined, first of all, by the reliability of establishing the elemental law of wear \( J(p, H, \varepsilon, \ldots) \), which includes the main parameters and the degree of their influence on the wear of materials. When one part is superimposed on another and pressed by force \( P \), the contact area \( S \) is formed, on which, as a result of the contact pressure \( p = P/S \) and the relative displacement of the conjugated bodies with velocity \( v \), the surface layers of the contacting materials are destroyed and the wear particles are separated. The dimensions of the contact area, the shape of the plot and the magnitude of the contact pressures depend on the geometry of the conjugated bodies, the mechanical properties of the materials, the loading conditions of the tribo-conjugation (load, sliding speed, temperature) and the amount of wear of the parts during its operation. For a number of structural materials with typical types of wear (abrasive wear, fatigue wear), such dependencies have been established [20]. The adequacy of the physical wear model to real processes occurring in the frictional contact is based on the choice of the elemental law of wear.

In order to adjust the amount of wear intensity determined by the results of tests on laboratory friction machines to the conditions of operation of a sliding bearing, it seems appropriate to present [20] the elementary law of wear in the form of a dimensionless complex:

\[
J = C f \frac{P_a}{P_r}
\]

where \( C \) – empirically determined constant based on laboratory wear test results; \( f \) – the coefficient of friction; \( P_a \) – the nominal pressure at the contact; \( P_r \) – the actual pressure. With a plastic contact characteristic of abrasive wear, it can be approximately assumed \( P_r \approx HB \).

The ability of a material to resist wear is mainly determined by the work of deformation (fracture) of the material in the zones of actual contact, which can be estimated by the characteristics of hardness and ductility of the material, namely, the product of \( HB \cdot \varepsilon_\tau \), i.e. the larger this product, the greater the wear resistance of the surface.

The ceramic material structure of the bearing bushing is shown in Figure 1.

![Figure 1. Microstructure of ceramics obtained from nanostructured zirconium oxide powders.](image)

The microstructure of the ceramic material consists of uniformly sintered grains smaller than (100-200 nm). Ceramic material obtained from nanostructured powders manufactured by ChMZ has good values of open porosity (0.01), transverse bending strength (500 MPa) and fracture toughness (6-8 MPa•m\(^{1/2}\)).
The type of tribological processes in the contact zone is affected by the type of friction unit (sliding bearing). When conducting experimental studies on friction machines, the loading parameters should provide physical similarity to the tribological processes in the friction zone of the model and full-scale units. A model friction unit in the form of a disk-finger interface (figure 2) simplifies the manufacture of test units, which is especially important for difficult-to-process ceramic materials, ensures constant average contact pressures and sliding speeds during testing, as well as free access of a gas or lubricant to the zone friction.

![Diagram of the model disk-finger friction unit.](image)

The design of the test allows the simultaneous study of three finger samples located symmetrically around the circumference at an angle of 1200. The steel disk-sample 1 (counterbody) is attached by screws 9 to the faceplate 6, which is connected by screws 8 to the rotating drive shaft 7 of the friction machine. Three crystalline finger samples 2 are mounted at an angle of 1200 relative to each other in the disc sockets — sample holders 3. The disk 3 is rigidly bolted 10 to the flange 5 of the stationary friction force meter. A support disk 4 is installed between the disk 3 and the flange 5, through which the load on the finger samples is transmitted.

Comparative tests of ceramic samples for friction are carried out for different materials of the counterbody (disk), grease is solidol. Table 1 shows the test results under sliding friction at an average contact pressure $p = 5$ MPa and velocity $v = 0.2$ m/s.

| Finger sample | Counterbody       | $J_{\text{finger}}$ | $J_{\text{disk}}$ |
|---------------|-------------------|---------------------|-------------------|
| Ceramic       | Steel U10 A       | $7.5 \cdot 10^{-8}$ | $5.7 \cdot 10^{-8}$ |
| (ZrO$_2$+ 3mol.%Y$_2$O$_3$) |                   |                     |                   |
| Ceramic       | Ceramic           | $6.0 \cdot 10^{-7}$ | $6.5 \cdot 10^{-7}$ |
| ZrO$_2$+ 17mol.%CeO$_2$ | ZrO$_2$, 17mol.%CeO$_2$ |                    |                   |
As a result of the experiments, it was found that finger samples made of material [ZrO$_2$ + 3 mol% Y$_2$O$_3$ ceramic] during steel friction wore 8 times less than finger samples made of [ZrO$_2$ +17 mol% CeO$_2$ material sintered] during friction on a ceramic disk made of materials of the same name.

Table 2 shows the results of calculating the reliability of a friction type bearing of a drive of a mixing device. The friction type bearing consists of a steel trunnion and a of zirconium ceramic bushing. Initial data: approximately it is considered that the shaft and the bushing have an elastic modulus of $E_1 = E_2 = 2 \cdot 10^5$ MPa; Poisson's ratio $\mu_1 = \mu_2 = 0.3$; nominal diameter $d_1 = 0.1$ m; initial clearance in the bearing $\varepsilon = 10 \ \mu m = 10 \cdot 10^{-6} m$; load $N = 50$ kgf = 500 N, speed $n = 100$ rpm, required life $T = 200$ hours, maximum wear $\Delta = 0.2$ mm. Ø10H$_6$ bushing made of zirconium ceramic, Ø10h$_6$ shaft Art. 45, TB4 HRC 48-50, the shaft rotates, the bushing is stationary. According to [21], for zirconium ceramics it was found that the wear rate of the bushings almost linearly depends on the load on the bearing.

Subject to amendments to the operating conditions of the bearing in question, the wear rate is $2.9 \times 10^{-9}$.

Table 2. Table of calculated data on determining the probability of failure-free operation of a friction type bearing.

| No. | Operation                              | Formula            | Result          |
|-----|----------------------------------------|--------------------|-----------------|
| 1   | Specific linear load                    | $P_L = \frac{N}{l}$ | $10^5$ N/m      |
| 2   | The loading coefficient according to the table [18] at $\beta = 0.028 \varphi_0 = 18^\circ$, where $\varphi_0$ - half the contact angle | $\beta = \frac{P_L}{\pi E} \left( 1 - \mu_1^2 + 1 - \mu_2^2 \right)$ | 0.028           |
| 3   | The maximum contact pressure, where $K_1 = 2.1$ (from the table for $\beta = 0.028$) | $P_{MAX} = 2K_1P$  | 42 MPa          |
| 4   | Medium pressure                         | $P = \frac{N}{d_1}$ | 10 MPa          |
| 5   | Contact pressure average                | $P_{AV} = \frac{P_L}{d_1 \sin \varphi_0}$ | 32.3 MPa        |
| 6   | Wear rate                               | determined experimentally ( $I_e$ ) | $2.9 \times 10^{-9}$ |
| 7   | The root-mean-square deviation of the limiting dimensions of the interface. Calculated by tolerances in the drawing of the part. | $S_h = \sqrt{S_B^2 + S_{BT}^2}$ | 2.12 $\mu$m     |
| 8   | The bushing is rejected according to the maximum size, where $\Delta$ - the maximum clearance | $d_{max} = d_0 + \Delta$ | 10.2 $\mu$m     |
| 9   | Part size variation coefficient         | $\nu_\Delta = \frac{S_h}{\Delta}$ | 0.0106          |
| 10  | The confidence interval for wear is one order of magnitude | $5.27 \cdot 10^{-9} > J > 0.53 \cdot 10^{-9}$ |                |
| 11  | Standard deviation                      | $S_i=(I_{max}-I_{min})/6$ | 0.70$\times 10^9$ |
| 12  | The coefficient of variation            | $\Omega=S/I_e$     | 0.34            |
| 13  | Sliding speed                           | $v = \frac{\pi d_1 n}{60}$ | 0.05 m/s        |
Safety factor for a given resource \( T = 200 \) hours

Quantile of normal distribution

By probability tables the probability of failure-free operation is found

The set value of reliability is mainly determined at the design stage. Designing with the given reliability of friction type bearings with new materials, in particular composite ceramic materials, requires consideration of many options. Experimental verification of all options is not economically feasible, therefore, bearing reliability calculations are an effective way to ensure machine uptime.

4. Conclusion

A methodology has been developed for calculating the life and reliability of friction type bearings with zirconium ceramic bushing operating in the conditions of boundary lubrication or dry friction. The calculation method is based on establishing the reliability of the elemental wear law \( J(p, H, \varepsilon \ldots) \), which includes the main parameters and the degree of their influence on the wear of materials.

Mechanical zirconium ceramics are investigated, the composition of the ceramic material with the highest crack resistance is selected, and the structure of the elemental law of material wear under the conditions of the friction type bearing is justified.

The calculation of the reliability of the friction type bearing, taking into account the real angle of coverage of the contact zone, variations in the dimensions and tolerances of the shaft and the bushing, the normal law of the distribution of errors, load and speed of the friction unit.

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