Methods of Evaluating the Wear Resistance of the Contact Surfaces of Rolling Bearings

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Abstract. In modern conditions of development of mechanical engineering, high priority is given to experimental and material science aspects of assessing the wear resistance of conjugate friction surfaces, which consist of the selection of materials with high wear resistance characteristics. However, this way, you can only reduce the intensity of the wear process, but not control the wear process itself and, most importantly, the changes in the state and performance of the mating surfaces that occur as a result of the wear process. The durability of machines is laid down at the design stage and depends on the design scheme, materials used, lubricants, and other factors. An increase in the durability of mated machine parts is impossible without creating modern engineering methods for calculating wear resistance, which would consider the physical and mechanical characteristics of materials (friction pairs, modes of operation of the load node, and angular velocity), external friction conditions (environment, and lubrication), as well as the design and technological features of the friction interface. During the wear of two contiguous bodies, the unevenness of one surface is exposed to the unevenness of the other surface. In this case, the irregularities of the more durable material act similarly to the abrasive elements, cutting off the thin chip from the micro-irregularities of the surface of the less durable material. At the same time, the irregularities that cut this chip wear themselves out, just as cutting abrasive tools wear out.

Keywords: Tests · Wear rate · Burn-in period · Roller bearing ring · Abbott-firestone curve

1 Introduction

The existing methods of the mathematical description of the wear of coupled machine parts can be divided into two groups. The first one is based on the physical and mechanical laws of wear, considering the influence of various factors on the wear process. The second one is based on the analysis of quantitative changes in the wear process without taking into account physical processes [1].

Using computational methods to find optimal design solutions can significantly facilitate the process of creating durable machines in terms of wear resistance of their

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parts [2, 3]. Using them, you can solve a number of scientific and practical problems. These problems are as follows: to choose and justify the optimal design parameters [4] of parts that provide a minimum wear rate; to set the limits of wear of parts; to select standard sizes of unified elements; to ensure uniform stability [5] of a node or part with several functional surfaces; assign wear-resistant materials and apply technological methods to strengthen them, justify the requirements for physical and mechanical properties; conduct a comparative assessment of the service life of parts (components), namely, several variants of design; predict the service life of parts based on the results of the short-term bench or operational tests [6–8].

2 Literature Review

A number of scientists [9–11] have developed analytical expressions describing the wear process (Table 1). However, they do not fully reflect all aspects of the wear process, due to the inability consider the specific contact of various tribological materials.

Table 1. Basic analytical expressions for determining the intensity of the wear process.

№	Expression	Type of wear
1	$J = \frac{\epsilon\, h_{max} A_r}{(v+1)\, d\, n_p A_c}$	Fatigue wear [7]
2	$J = \frac{h\, A_r}{(v+1)\, d\, n_p A_c}$	Mechanical wear [7]
3	$J = \frac{\rho\, \psi\, l\, P}{P_{cp}\, K\, \phi}$	Abrasive wear [7]
4	$J = \frac{tg\theta\, p}{6\, P}$	Mechanical wear [8]
5	$J = \frac{\pi h^2 (R - \frac{h}{3})\, n_a}{A_a\, d\, n_p}$	Abrasive wear [8]

Note: A_r and A_c – actual and contour contact area; P-load; h_{max}, tgθ, v – surface roughness parameters; H – hardness; ρ – density; P_{cp}, P_a – average and nominal pressure; f – coefficient of friction; I – the path of friction; R-gas constant; T – absolute temperature; ψ, n, r, k, λ, φ – empirical coefficients; ε – relative deformation; d – diameter of the contact zone

For the confirmation of the theoretical assumptions, tribological machines are used for durability tests. For kinematic characteristics, all installations for tribotechnical testing of materials are divided into two classes: unidirectional and alternating relative movement. Within each class, the installations are divided into two groups: face friction machines and friction contact machines, in each group two more subgroups are distinguished: by the coefficient of mutual overlap K_{mo}, so there are two boundary cases: $K_{mo} \rightarrow 1$ and $K_{mo} \rightarrow 0$, in practice, test machines are used, the diagrams of which are presented in Fig. 1 [2, 9, 10, 12].

We introduce the following notation, in the case of $0.5 < K_{mo} < 1$: for a – unidirectional end friction; fib – unidirectional friction on the formation; c – alternating end friction; d – alternating friction on the formation.

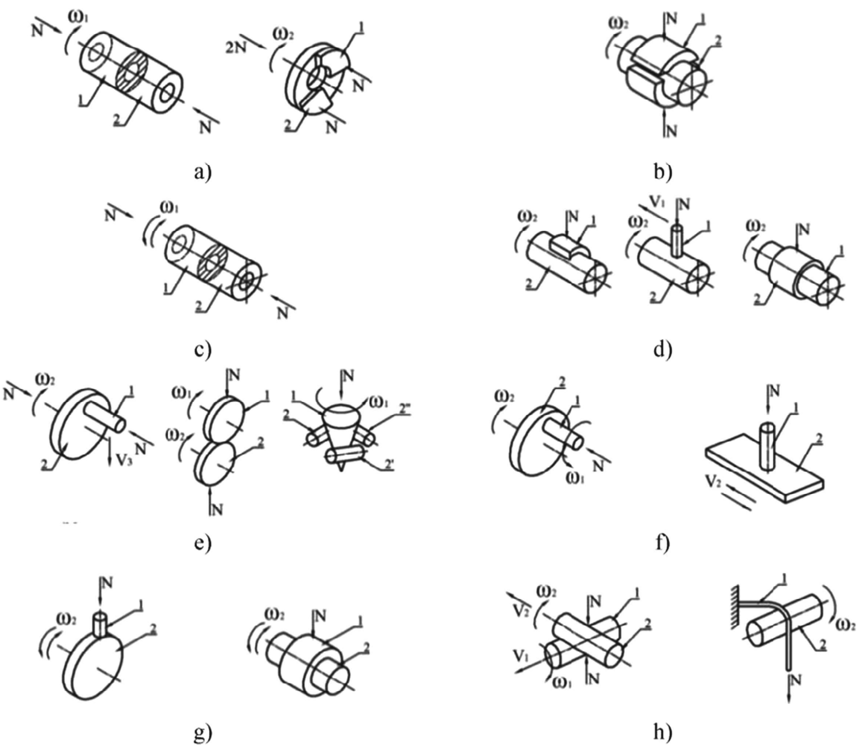

Fig. 1. Kinematic schemes of installations for determination of durability.

In the case of $0 \leq K_{mo} < 0.5$: for d – unidirectional end friction; h – unidirectional friction on the formation; same f – alternating face friction; g – alternating friction on the formation. The main criteria for evaluating tribotechnical characteristics are the wear intensity (wear resistance criterion) and the coefficient of friction (the criterion of mechanical losses during friction – the ratio of the friction force to the value of the normal force. The wear rate is the ratio of the thickness of the destroyed layer of material to the path where friction occurred:

$$I = h / L \tag{1}$$

where h – the value of the destroyed layer, mm, for the friction path L, mm, under specific regulated test conditions (lubricants, presence of abrasive, sample temperature, loads).

3 Research Methodology

For the assessment of the wear resistance of materials, the wear intensity of each sample of the friction pair is determined based on formula 1. But to consider the structural and tribotechnical properties of different types of friction pairs, let us consider different variations of the ways of contact of parts and movement of test equipment according to the classification given in Fig. 1.

For samples with a smaller surface of reciprocating friction pairs (sample 1, e.g., piston, and ring) for the test period with the number of cycles n:

$$I_1 = h / 2nH = \Delta q / 2\rho nHbl_{k1} = \Delta q_1 / 2\rho_1 nHA_a \tag{2}$$

where h1 – worn layer of sample 1 for n cycles; Δq1 – mass loss of sample 1 for n cycles; H – move rolling sample; 2H – friction path for all points of the friction surface of sample 1 during the cycle; l – the size of sample 1 in the direction of the relative displacement; b – the size of the sample in the direction perpendicular to the relative movement; what characterizes the nominal area of contact of the friction pair; $A_a = l_k$ b – nominal contact area pair (the working area of sample 1); ρ is the density of sample 1.

For samples 2 with a larger friction surface, such as a sleeve, during the test period with the number of cycles n, the wear intensity is defined as follows:

$$I_1 = h_2 / 2nl_k = \Delta q_2 / 2\rho_2 nl_2 bH = \Delta q_2 / 2\rho_2 nHA_a \tag{3}$$

where $2l_k$ – the greatest way of friction on the surface of sample 2 in one cycle; h_2 is the mean value of worn-out layer of sample 2 over n cycles; Δq2 – mass loss of sample 2 for n cycles; ρ_2 – the density of sample 2.

For friction pairs of rotational motion according to the “pad-roller” scheme, when determining the mass loss of each of the samples, the wear intensity is determined using these formulas.

For pads for the test period with the number of revolutions n:

$$I_1 = h_1 / L_1 = \Delta q_1 / 2\pi RnF\gamma_1 \tag{4}$$

where h1 – worn layer of the sample for n turns (taken uniformly on the friction surface of the sample); Δq1 – mass loss of the sample in n revs; L 1 = 2πRn is the path of friction of the sample in n of turns; R is the radius of the roller; F = bl – of the nominal contact area pair; l – the sample size-pads in the direction of the relative displacement; b – the sample size-pads in the direction perpendicular to the relative movement; γ_1 is the specific density of the material of the sample pad.

For the roller sample during the test period with the number of revolutions n, the wear intensity is equal to:

$$I_2 = h_2 / L_2 = \Delta q_2 / 2\pi Rnb\gamma_1 \tag{5}$$

where h_2 – the average thickness of the worn layer of the sample clip for n revolutions; $L_2 = l$ is the maximum path friction points of the sample surface of the roller in one revolution; Δq_2 – mass loss of the sample-roller n speed; γ_2 is the specific density of the material sample clip.

At end friction:

$$I = \Delta h / 2\pi r_{av} n \tag{6}$$

where Δh – average linear wear for n test cycles; r_{av} – the average radius of the contact area; n – the total number of revolutions of the sample.

In the case of wiping the socket with a cylindrical sample on a flat sample when measuring the total wear, the average wear intensity during the increase in the number of revolutions n_i is calculated using the formula:

$$I_{hi} = hi/30\pi n_i \tag{7}$$

where hi – the average value of the displacements, mm.

In addition to the wear rate, the test results are evaluated using the relative wear resistance, that is, by weighing samples before and after the tests, thereby determining the average arithmetic value of the mass loss g_{st}, reference samples and the average arithmetic value of the mass loss of samples of the test material g_{ts} (8, 9):

$$g_{st} = \frac{\sum_{i=1}^{m} g_{sti}}{m}, \tag{8}$$

$$g_{ts} = \frac{\sum_{i=1}^{m} g_{tsi}}{m}, \tag{9}$$

where g_{sti} , g_{tsi} – mass loss, g, during testing of reference samples and samples of the test material, respectively; m – the number of samples of the test material.

The relative wear resistance of the material under study is expressed as:

$$K_{WR} = (g_{st} \cdot \rho_{ts} \cdot n_{ts}) / (g_{ts} \cdot \rho_{st} \cdot n_{st}) \tag{10}$$

where ρ_{st} , ρ_{ts} – density of the reference and test materials, respectively, g/cm^3 ; n_{st} , n_{ts} – the number of revolutions of the roller during testing of the reference and test materials.

During the measurement of sample sizes before and after testing, the relative wear resistance is determined using the formula:

$$\epsilon = \Delta h_{st} / \Delta h_{ts} \cdot (d_{st} / d_{ts})^2 \tag{11}$$

where Δh_{st} – absolute linear wear of the reference sample; Δh_{ts} – absolute linear wear of the test sample; d_{st} – the actual diameter of the reference sample; d_{ts} – the actual diameter of the test sample.

The effect of the longitudinal feed (or a value proportional to the thickness of the removed metal layer) during machining, is expressed as follows:

$$J = H_{max} = H_p + H_y \cdot \left(1 - \frac{s^2}{2R^2}\right) \tag{12}$$

where H_{max} – the real height of the micro-irregularities, in microns; H_p – the calculated height of the irregularities obtained from the geometric dimensions of the tip of the cutter; H_y – elastic recovery of metal after removal of load from the indenter; s – longitudinal flow; R – the radius of the tip of the cutter.

The nature of the dependence H_{max} = f(s) during cutting is, to some extent, similar to the nature of the dependence of wear on the specific load, if the tangent surfaces have a different micro geometric structure, that is, different height and pitch between adjacent irregularities.

Table 2. Values of the parameters of the reference surface curves for transverse and longitudinal roughness.

v_1	1	2	3	2
v_2	1	1	1	2
A_{r2}/A_{r1}	2	3	4	5.87

Studies of the wear process and determination of the burn-in period were performed by the installation VNIPP-542 (Fig. 2).

Fig. 2. Installation of VNIPP-542 to test the wear resistance of bearings.

Tests were performed on new roller bearings. The experiment ended when the bearing began to collapse. Thus was determined by the period of stable operation of the roller bearing, depending on the method of finishing.

The samples are used roller bearings of the 700 series (steel 100Cr6, hardness HRC 60–62), which were made according to various finishing technologies with the microstructure of martensite and carbides [13–15]. For testing 5, gradations of purity of treatment were taken. The first sample was made by the method of hardening-smoothing treatment (height of inequalities 0.2 µm). The remaining four samples were prepared by necessary technology as superfinishing with the height of micro-inequalities 0.8; 1.5; 3, and 6 µm. The inner and outer rings had the same roughness.

If the material densities of the reference and test samples are equal, the ratio of absolute linear wear in formula (11) may be replaced by the ratio of absolute wear of the mass.

4 Results

Thus, it would be justified to say that wear is the same chip removal process as other abrasive machining processes [1, 16]. The only difference is that the machining is performed with a cutting tool with a controlled geometry (deterministic approach), and the treated surfaces are regularly located irregularities of the same size, one layer of chips is removed in one pass (stochastic approach). During the wear process, the irregularities of the contact body of the stronger material have a stochastic geometric shape on the destroyed surface after burn-in, the irregularities remain in random order. Besides, during wear, the phenomenon of molecular setting has a determining effect. Therefore, for the characteristic of wear resistance, the dependencies for the abrasive processing processes will be set fair [17, 18]. If you select the prevailing factors that affect the wear process, the effect of these factors will be the same as the effect of similar factors in the process of cutting metals.

The dependence of $H_{max} = f(s)$ is expressed by a logarithmic curve (Fig. 3), which for values $s = R\sqrt{2}$ rises above the curve $H_p = f(s)$, and at a point intersects with this curve and goes down. Thus, it is fair to say that if you feed less than the real height of asperities higher than the calculated height H_p, and after the specified flow value of H_{max} is less than H_p.

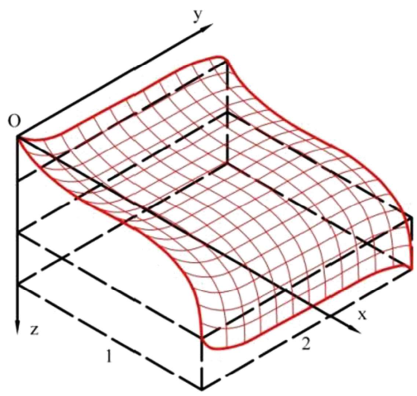

Fig. 3. Scheme for constructing a reference curve of the Abbot-Firestone surface: 1 – transverse profile of the curve (ox); 2 – the longitudinal profile of the curve (oy).

One of the most common methods for evaluating the microgeometry of the surface layer of solids is the construction of the reference surface curve (Abot-Firestone curve). This curve characterizes the filling of zones of the normal cross-section of a solid body with material located between parallel lines drawn along the body profile [16, 19]. The most objective characteristic is the curve of the dependence of the material filling zones of the surface of a solid formed by planes parallel to its surface. In [10], recommendations are given for experimentally obtaining such a dependence. This method involves the construction of transverse and longitudinal curves of the reference surface. The abscesses of the obtained curves corresponding to the same level are multiplied to obtain the values of the cross-section areas. It is well-known that depending on the processing method, there is either a specific orientation in the location of micro-steps and their shape or an isotropic geometric structure for all directions. A clear focus is observed during turning, milling, and grinding. The isotropic distribution of protrusions is typical for polishing and strengthening-smoothing treatment [12]. The curves of the support surface in the case of an isotropic distribution of protrusions are the same for all directions. And the cross-sectional area of the material at this level corresponds to the square of the abscissa of the support surface curve. An example of such a surface is shown in Fig. 3.

The equations of curves of reference surfaces in their initial part can be represented as:

$$\begin{aligned} x &= b_1 z^{v_1}, \\ y &= b_2 z^{v_2}, \end{aligned} \tag{13}$$

where b_1, v_1, b_2, v_2 – parameters of support surface curves for transverse and longitudinal roughness. Given (13), the equation of the cylindrical surface will take the form:

$$z = \frac{1}{b_1^{\frac{1}{v_1}}} x^{\frac{1}{v_1}} + \frac{1}{b_2^{\frac{1}{v_2}}} y^{\frac{1}{v_2}}. \tag{14}$$

The dependence (14) allows you to determine the cross-sectional area of the material at a given level z. In Table 2 shows the value of the cross-sectional areas of the material defined using the formula (14) – Ar_1 according to the given Ar_2 method.

After testing, the volume of removed metal was determined using a research facility based on the model 201 Profiler. Profilograms were taken from the forming functional surfaces of the rings. The probe of the Profiler first moved along the unworn part of the surface layer, then along with the worn one. The particular type of the profilogram determines the volume of worn metal. During the tests at the VNIPP-542 installation, the following modes were set: F_a = 21 kgf/cm^2, F_r = 12 kgf/cm^2 (axial and radial loads, respectively); n = 6000 rpm; T = 0.5–15 h. 10W-40 oil with 10 drops per minute was used as a lubricant. For each of the 5 grades of purity, 10 identical samples were taken, which were tested in the installation for 0.5–15 h. A total of 50 control points were obtained, the location of which is shown in Fig. 4. The nomogram shows the mass of the cut material in grams along the ordinate axis, the test time in hours along the abscissa axis (to the right), and the maximum height of irregularities in the roller bearing rings on the applicant axis (to the left). The nomogram shows that the dependence of wear J during the burn-in period on the surface layer roughness (H_{max}) is expressed for all H_{max} values by a line that intersects the ordinate axis above the origin point.

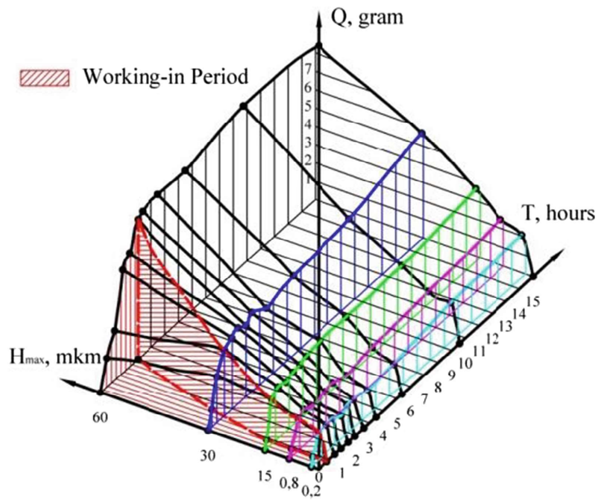

Fig. 4. Nomogram for determining the period of wear of friction surfaces by the amount of material removed due to wear.

The dependence of wear on the duration of tests for all grades of surface layer purity is approximately the same.

5 Conclusions

The proposed dynamic calculation is based on the analysis of the mechanism of the process of destruction of parts under different types and modes of friction and allows obtaining approximate wear rates of various materials and their interfaces. The value of this method also lies in the fact that, based on the calculated data, it is possible to lay the foundations of high wear resistance of friction pairs at the design stage. It was found that the amount of wear increases sharply during the first 0.5–2.5 h, and then growth slows down. The burn-in area, when the micro-roughness of the machining is cut off, is shown in Fig. 4 is marked in red and shaded. In this area, wear largely depends on the burn-in time. If the radial load wear is very high and does not rely on the microgeometry of the contacting surfaces, then a mathematical description of the wear phenomenon is carried out based on the results of processing data obtained during operation. Experimental data confirm the proposed method for analyzing the wear resistance of the mated surfaces of parts to ensure the maximum duration of the period of stable operation by assigning technological modes of mechanical processing. It can be used in the design of technological processes for manufacturing parts.

It is planned to develop a technology for machining the parts of the bearings, which will minimize the working-in period. This will allow the machines to be operated immediately at rated modes bypassing the running-in period.

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