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Simulation of the tribological properties of motor oils by the results of laboratory tests

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Abstract: The purpose of this work was to create a calculation-experimental method for calculating the wear of lubricated friction units of machines based on a two-factor wear model (contact pressure – sliding velocity) with identification of their wear resistance parameters. To achieve this purpose it was necessary to obtain theoretical dependences for identification of wear resistance parameters in the wear models based on laboratory tests with various geometrical contact diagrams of lubricated samples. Analysis of known studies has shown that existing approaches required solution of complex systems of integral-differential equations or numerical methods that are unacceptable in the engineering practice. In this work a model of the wear of lubricated friction units of machines in conditions of boundary friction was obtained in a form of dependence of the wear rate on the dimensionless complexes of contact pressure and sliding velocity. The basis was the solution of the inverse wear of the contact problem for various geometrical schemes of contact. The contact diagrams corresponded to the actual forms of contact of the friction units of the machines: rolling bearings and sliding bearings, gears and others. The following equations were taken as the defining equations: the equilibrium equation in the contact, the continuity equation in the contact, and the approximating experimental dependence for the wear of materials. As a result of the solution, it has been obtained the simple algebraic formulas for calculating and identifying the parameters of the patterns of wear. It was realized that the installation has been developed for tests by means of program Solid Works and the numerical algorithm of the decision of a task on the basis of program MathCad. During the work it has been studied the influence of determining factors of sliding velocity and load on bearing wear. The obtained results were recommended for predicting wear of lubricated friction units of engines at the design stage and optimizing their design and operational parameters.

Keywords: wear, lubrication, laboratory testing scheme, problem of contact wear, contact pressure, engine.

1. Introduction

The main reason of the breakage of the units of friction of the machines is wear process. The lubrication is the most effective way to increase wear resistence of friction units of machines. Therefore the first basic task of the researchers, designers and technologists is the creation of conditions of preservation and restoration of lubrication in contact. The success of researches of wear process of the lubricated surfaces is determined by test methods. Among known test methods of friction units with lubrication the most perfect are tests which are under the four-ball scheme. This is standard method and it is widely applied all over the world [1]. The main defect of the test is absence of the mathematical

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description of the wear process on this scheme. It brings only to qualitative description of the process. Besides four -ball test it has been used only standard material from become 52100 steel balls. But scheme of the external contact two balls not adequately prototypes the contact of the real interfacing the of friction units of the machines. In this connection it was put problem in given work to give the quantitative description of the wear process samples for different schemes of the tests and materials. The base of the decision of the problem there is decisions direct and inverse war conact tasks for contact and wear samples of the different form [2-4]. And as a result it was received the mathematical models of the wear process with using the accounting programs.

In work [2] analysis of variation of the contact pressure during wear was carried out at a nonlinear form of the wear. It was taken the dependence of wear rate on the factors of velocity and contact pressure. As a result it has been proposed the algorithm for solving the wear-contact problem for the thrust bearing.

It has been made in the solution of an inverse wear-contact problem for identifying parameters of the wear rate on contact pressure and sliding velocity [3]. It was derived the expressions for determining wear parameters on the basis of experimental dates of wear. But the assumption of permanence of the wear according to the test didn`t let us use this solution for the test schemes with a variable contact.

In paper [4] it has been carried out the theoretical analysis of kinetics of wear of spherical specimens on a four-ball tests friction machine. It was made the equation of wear kinetics corresponds to differential equation. But the described kinetic model has a phenomenological character with the principles of open thermodynamic systems.

In work [5] it is presented the theory of ball wear for a four-ball wear testing scheme While this work it has been solved the direct problem of determining the dimensions of the worn place depending on the sliding distance and the inverse problem of determining the parameters of the wear model based on the data of wear tests. Solutions have been obtained for the initial zero and nonzero contact patch and they are based on the assumption of a uniform distribution of the pressures over the contact area. It has been provided the examples of numerical solutions of the problem of contact wears under consideration.

In work [6] it was considered the problem of developing a calculation-experimental method for calculating wear of a sliding bearing based on a two-factor wear model with identification of wear resistance parameters To identify parameters of wear resistance in the wear model, a calculation-experimental method for determining calculated dependences of wear resistance parameters was developed on the basis of the wear test by the "cone - three balls" scheme.

The task of this work was to create a calculation-experimental method for calculating the wear of lubricated friction units of machines which were based on a two-factor wear model (contact pressure – sliding velocity) with identification of their wear resistance parameters. As a result, it was necessary to obtain theoretical dependences for identification of wear resistance parameters in the wear models based on laboratory tests with various geometrical contact diagrams of lubricated samples.

2. Technique of construction of models of wear process on an example of the four-ball scheme

The scheme of tests is considered at which top sphere rotates and bases with effort Q to three motionless bottom spheres (Fig. 1). As a result of tests a is formed for the bottom spheres the circular platform of wear process of radius. It is neglected the influence of elastic deformations of spheres on formation of a platform of contact. The zone of contact top and the bottom spheres is filled by the lubricant material.

The model in the form of dependence of intensity of wear process on two parameters is accepted for the description of the wear process of the bottom spheres under the accepted scheme of test. These parameters are loadings and speeds of sliding:

$$I = \frac{du_w}{dS} = k_w \left(\frac{\sigma}{E^*} \right)^m \left(\frac{VR^*}{\nu} \right)^n , \tag{1}$$

where σ – contact pressures; E^* - the resulted module of elasticity of materials of contacting spheres; V - the relative speed of sliding; R^* - the resulted radius of contacting spheres;

ν - the kinematic viscosity of a lubricant (at 100°C); u_w - the linear wear of the bottom spheres; S - the way of friction for the bottom spheres; k_w, m, n – the parameters of model of wear process.

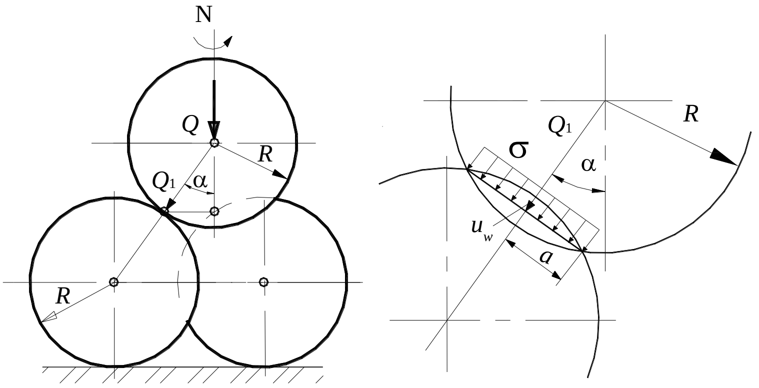


Figure1. Scheme of four-ball wear test.

Dependence of linear deterioration u_w on radius of a platform of wear process a of the bottom spheres is defined from geometry of crossing of spherical surfaces (Fig. 1):

$$u_w(S) = \frac{a(S)^2}{2R}. \tag{2}$$

From tests it is possible to receive the dependence of radius of a circular platform of wear process on a way of friction in the form of sedate approximation:

$$a(S) = cS^{\beta}, \tag{3}$$

where c, β – the parameters of approximation.

At uniform distribution of contact pressure on a platform of contact from a condition of balance in contact of spheres it will be received such formula:

$$\sigma = \frac{0{,}4082Q}{\pi a^2}. \tag{4}$$

After substitution (2-4) in (1) and integration, we shall receive:

$$\frac{c^2 S^{2\beta}}{2R} = K_W \left(\frac{0{,}4082Q}{c^2 \pi E^*}\right)^m \left(\frac{VR^*}{\nu}\right)^n \frac{S^{1-2\beta m}}{1-2\beta m}. \tag{5}$$

Whence m from a condition of feasibility of the equation (5) at any S it will be determined:

$$m = \frac{1-2\beta}{2\beta}. \tag{6}$$

For a finding of parameter n tests are spent at two values of speed of sliding V_1 and V_2 and two groups of data with parameters receive:

$$a = c_1 S^{\beta_1}; \quad a = c_2 S^{\beta_2} \tag{7}$$

It has been considered the problem of determining parameters of wear according to the results of testing specimens with the contact area changing in the process of wear. The change of the wear area causes the change of the contact pressures. The parameter m in expression characterizes the rate of change of contact. It is related to the parameter β of the experimental dependence (3) which is characterized by the of change of the contacting area during wear. The relationship between m and β in the model of wear (1) is uniquely described by relation. Since the sliding velocity V in the considered ratios it does not depend on the friction path S, it does not affect parameters n and β during the tests. In this case, the change in the slip velocity V affects just the scale factor c in expression (1). The above reasoning is confirmed by the test results.

At constant test specifications for the wear process $\beta_1 = \beta_2 \approx \beta$ is accepted. Substituting expressions (7) in (5), we shall receive system of two equations:

$$\left.\begin{aligned} \frac{c_1^2 S^{2\beta}}{2R} &= K_W \left(\frac{0,4082Q}{c_1^2 \pi E^*}\right)^m \left(\frac{V_1 R^*}{\nu}\right)^n \frac{S^{1-2\beta m}}{1-2\beta m} \\ \frac{c_2^2 S^{2\beta}}{2R} &= K_W \left(\frac{0,4082Q}{c_2^2 \pi E^*}\right)^m \left(\frac{V_2 R^*}{\nu}\right)^n \frac{S^{1-2\beta m}}{1-2\beta m} \end{aligned}\right\} . \qquad (8)$$

For definition of parameter n we shall divide the first equation into the second and after transformations we shall receive:

$$n = (2m+2)\frac{\lg(c_1/c_2)}{\lg(V_1/V_2)} . \qquad (9)$$

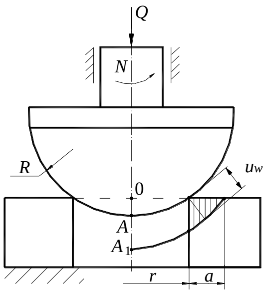
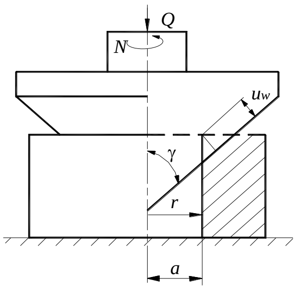
For a finding of factor K_w we shall take advantage of one of the equations (8):

$$K_w = \frac{\beta c_1^{2m+2}}{R}\left(\frac{2\pi E^*}{0,4082Q}\right)^m \left(\frac{\nu}{V_1 R^*}\right)^n . \qquad (10)$$

As a result of the solution, simple algebraic formulas for calculating and identifying the parameters of the patterns of wear have been obtained.

3. Results of modelling of wear process at tests under schemes: a sphere-ring, a cone-ring

Table 1. The schemes of tests and parameters of models of wear process.

Parameters	Ball – ring	Cone – ring
		
m	$m = \frac{1-\beta}{\beta}$	$m = \frac{1-\beta}{\beta}$
n	$n = (m+1)\frac{\lg(c_1/c_2)}{\lg(V_1/V_2)}$	$n = (m+1)\frac{\lg(c_1/c_2)}{\lg(V_1/V_2)}$
K_w	$K_w = \frac{\beta c_1^{m+1} r^{m+1}}{R}\left(\frac{2\pi E^*}{Q}\right)^m \left(\frac{\nu}{V_1 R^*}\right)^n$	$K_w = \beta c_1^{m+1}\cos\gamma\left(\frac{2\pi r E^*}{Q}\right)^m \left(\frac{\nu}{V_1 R^*}\right)^n$

The scheme of contact of four spheres is used for test interfaces of non-similar form from steel materials (gearings, cam mechanisms, bearings, etc.) Using testing materials of sliding bearings, including polymeric for interfaces of the similar form (sliding bearings, hinges, etc.) the sphere - a ring is offered to use for tests the scheme. The third scheme of tests a cone - a ring is offered for expansion of types of tests of constructional materials Manufacturing of the conic sample more simple, than manufacturing of a sphere. It has been used the form (1) as the general form of model of wear process The schemes for calculation and results of definition of parameters of models of wear process are shown in Table 1.

4. The device for tests

Wear tests can be performed for a variety of purposes, in particular: a qualitative comparison of lubricants and construction materials for wear; study of the mechanism and type of wear; definition of model parameters which describe the quantitative laws of the process. Here we consider the methods of laboratory testing for wear with the determination of the parameters of wear models, with the help of which in the future it becomes possible to estimate the estimated wear of real lubricated friction units of a car.

For quantitative definition of parameters of models of wear process by results of laboratory researches the device for tests on the basis of four - ball machines of friction has been designed by means of program Solid Works (Fig. 2). The basic unit of the device is the working unit (Fig. 2). The top sphere 1 is based on the aperture of the end of a spindle. It does not suppose palpation of a sphere at rotation and increases rigidity of unit. The bottom three spheres in 2 diameter of 12.7 mm are installed on tempered surface of a support 4.

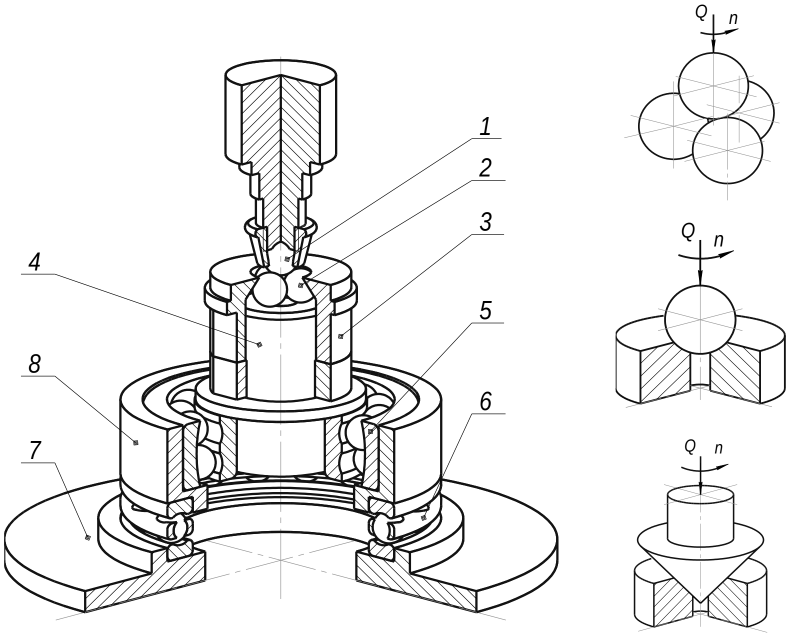


Figure 2. The device for tests (Solid Works).

The top plane of a nut 3 is used as measuring base for measure size of wear. The wear is measured without disassembly of the device. The microscope MPB-2 with by division of 0.05 mm is used for measurement of the sizes of spots of wear process on the bottom spheres. After measurements of wear process of test proceed under the accepted program. Exception of skews and self-installation at contact of spheres is provided with spherical bearing 5. The persistent bearing 6 is used for measurement of the moment of friction. The top sphere is loaded by means of the lever with the transfer attitude k =3.25. The thermometer of it is applied to the control of temperature to a zone of friction of spheres. A sensitive element of the thermometer (pos. 9, Fig. 2) is placed in a support under the bottom spheres. During these tests it has been carried out the continuous control of temperature of greasing over a zone of friction.

5. Results of tests of lubricant and constructional materials

Initial data:

The scheme 1. Four balls.

1. $R = 6{,}35$ mm.
2. $Q = 65$ N .
3. N_1 =200 rev/min (V_1 = 0,077 m/s), N_2 =600 rev/min (V_2 =0,19 m/s).

4. A material of balls: steel 52100.
5. A lubricant - motor oil Formula Q8, ν =12 mm²/s (API- SJ/CD, SAE - 15W/40).

The scheme 2. Ball-ring.

1. $R = 6{,}35$ mm, $r = 3$ mm
2. $Q = 65$ N
3. N_1 =200 rev/min (V_1 =0,063 m/s), N_2 =600 rev/min (V_2 =0,19 m/s).
4. A material of a ball - steel 52100; rings - aluminium.
5. A lubricant - motor oil Formula Q8, ν =12 mm²/s (API- SJ/CD, SAE - 15W/40).

The scheme 3. Cone-ring.

1. $\gamma = 30^0$, r =3 mm.
2. $Q = 65$ N .
3. N_1 =200 rev/min (V_1 =0,063 m/s), N_2 =600 rev/min (V_2 =0,19 m/s).
4. A material of a cone - steel 45; rings - bronze CuSn10P.
5. A lubricant - motor oil Formula Q8, ν =12 mm²/s (API- SJ/CD, SAE - 15W/40).

After tests under three specified schemes the results presented in table 2 have been received.

Table 2. Dependence of the sizes of a platform wear processes *a* (mm) from duration of tests (numerator-200 rev/min, a denominator-600 of rev/min).

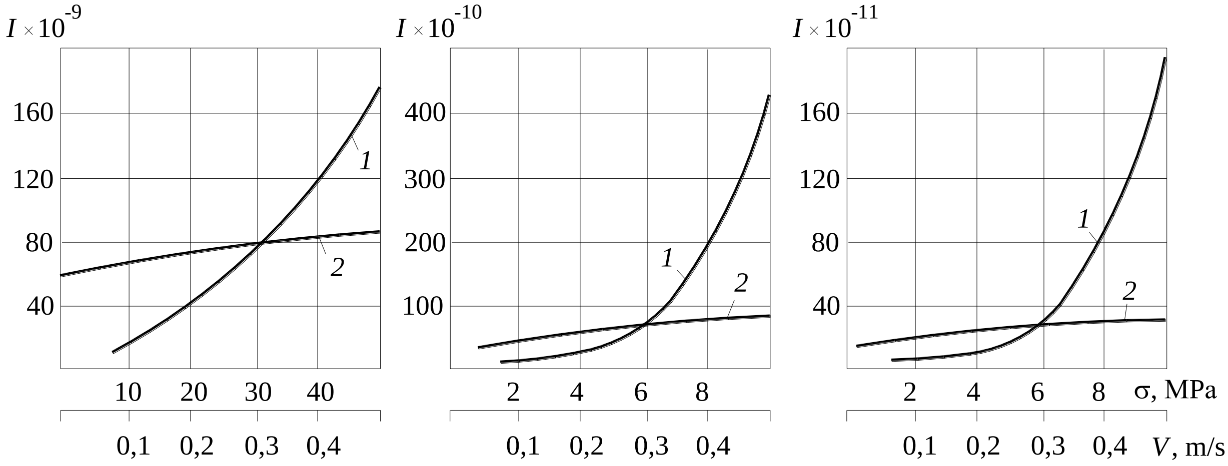
Scheme	30 min	60 min	90 min	120 min	150 min	180 min
1	0.35	0.4	0.43	0.48	0.5	0.51
	0.48	0.54	0.63	0.65	0.67	0.68
2	0.125	0.2	0.25	0.275	0.35	0.4
	0.25	0.35	0.4	0.475	0.5	0.5
3	0.125	0.2	0.225	0.25	0.275	0.3
	0.225	0.325	0.375	0.4	0.425	0.45

Results of tests have been processed by means of programs Excel and MathCad. The calculated parameters of models of wear process for three schemes of tests are presented in Table 3.

Table 3. The models of wear.

Four balls	$I = 0{,}025\left(\frac{\sigma}{E^*}\right)^{1{,}62}\left(\frac{VR^*}{\nu}\right)^{0{,}135}$
Ball - ring	$I = 4{,}7\cdot 10^7\left(\frac{\sigma}{E^*}\right)^{4{,}19}\left(\frac{VR^*}{\nu}\right)^{0{,}441}$
Cone - ring	$I = 2{,}19\cdot 10^8\left(\frac{\sigma}{E^*}\right)^{4{,}37}\left(\frac{Vr}{\nu}\right)^{0{,}403}$

In Fig. 3 it is shown the dependences of intensity of wear process on contact pressure (1) and speed of sliding (2) for three schemes of the tests, which were constructed on models (Table 3).



Four balls Ball-ring Cone-ring

Figure 3. Dependences of intensity of wear process on contact pressure – 1 and speed of sliding – 2.

The received technique of construction of models of wear process can be used for designing units of friction and optimization of their parameters.

6. Conclusions

Test of lubrications by the four-ball machine without definition of models of wear process, has qualitative character. Also it can be used only for the limited types of materials and forms of interfaces.

The wear test methods are offered to three schemes with definition of parameters of multifactorial models of wear process. It is designed by means of program Solid Works the device for tests.

The numerical algorithm is developed for calculation of parameters of models and comparison of properties of lubricants for units of friction by means of program MathCad.

The obtained patterns of wear allow us to quantify the value of the intensity of wear depending on: load characteristics, properties of structural and lubricant materials, kinematic and design parameters. Quantitative values of the wear rate allow you to optimize the values of the specified parameters and operating conditions of tribo interfaces by the criterion of maximum durability.

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