Estimation of Rolling-Contact Bearings Operational Properties by Electrical Probe Method

O.Rekhlitsky[1], S.Korotkevich[2], N.Solovei[3], D.Rekhlitskaya[4]

[1,3,4]JSC "STCCE"., Gomel, Belarus
[2]RUP Gomelenergo, Gomel, Belarus

Abstract— *The substantiation of an electrical probe method using for diagnostic real bearing units on a boundary state is given. The circuit diagram is developed and the way of estimation tribological properties of rolling-contact bearing races surfaces by means of electrical probe methods is offered. Correlation between parameters of conductance, mechanical strength and frictional metal surface characteristics is installed. It is shown, that application of the given methods allows to control the rolling-contact bearing state.*

Keywords— boundary lubricating layer (BLL), metal surfaces, contact resistance, dislocation structure, fracture mechanisms and surface deterioration, rolling-contact bearing.

I. INTRODUCTION

Reliability and durability of agricultural machinery rolling-contact bearings are defined by many factors: bearing steel quality, form and a roughness of balls, inner and outer races, type of their heat treatment, total product design (for example a grain harvester straw rake) assembly technology and unit adjustment, and also antifriction and strength properties of greases [1]. Durability of the rolling-contact bearing is defined by million cycles of multicyclic frictional loading [2].

The analysis of a boundary state means a metal surface state control without lubricant presence on it and interconnection determination between state and tribotechnological properties, and reinforcement and destruction of a metal surface kinetics [3].

Insufficient lubricant ability BLL in tribological conjunction leads to runout of grease from a contact zone in the beginning, and then under the influence of multicyclic and, as a rule, low amplitude tensions, on real contact points microcracks are formed. Fretting fatigue occurring at very small oscillatory amplitudes when only incipient sliding is present, i.e. the contact area includes both, stick and slip zones [4]. Microcracks increase in size and under the influence of multicyclic fatigue unit and form macrocracks that leads to material separation from a body surface in the form of a petal [5]. Proceeding activity of low amplitude tensions leads to formation of developed dislocation structure on the surface, to its dispersing, that causes petal-scaly wear of material [6]. On a place of the separated material, on a surface pits, tears, hollows are formed, i.e. processes typical for pitting proceed. Energy pumping in the material subsurface layers at a multicyclic frictional loading leads to interacting dislocation accumulations and their exit that promotes pores and strips sliding formation [7]. Progressing ripping of the metal surface layer, related with increasing of fractures nucleus number occurs. At a stage of the maximum dispersing this ripping, covering deeper layers causes sharp increasing exfoliated material mass in the form of the total layer. This process acquires ripple character and leads to selective emissions of destruction products from a frictional contact zone [8]. Selective wearing mechanism of material great volumes leads to scuffing, dripping of mated surfaces, separator destruction and bearing wedging.

Forage- and grain-harvesting techniques work seasonally. Terms of grain harvesting and various root crops, preparations of forages are restricted. In this connection any idle time of agricultural machinery leads to considerable material losses. Therefore minimizing of the idle time related with repairing and working capacity restoration of the failed rolling-contact bearings is the important problem at techniques designing.

The work purpose is an analysis of rolling-contact bearings working capacity and criteria of their work regimes estimation with using of an electrophysical probing method.

II. EXPERIMENTAL TECHNIQUE

It is possible use following way to estimate an operating mode of the rolling-contact bearing state, an outer race of which, as a rule, is motionlessly fixed in the harvester unit, and the inner race is on the rotating axis.

The way consists in calculation of contact resistance value (R_c) between racers on the basis of Hertz theory relationships [3]. We will make an example theoretical calculation. In the capacity of an object of research was rolling-contact bearing ZVL 6302/16 manufactures Slovakia with an external diameter of a race 42 mm and an inner race diameter 16 mm is taken. Width of races is 13 mm. Diameter of a ball is 8 mm. Quantity of balls is 7 pieces. The way width of an inner and outer race is 6 mm.

For methods of electrical probe the question on definition of the actual square of contact rubbing solids has key value. Calculation of the nominal contact square of the conjugate solids is carried out from relationships of the classical Hertz theory. The contact ball square (S) with a racer makes an ellipse with semiaxises a* and b (figure 1) where the major semiaxis a* is directed perpendicularly to a rolling motion way (a rolling motion direction).

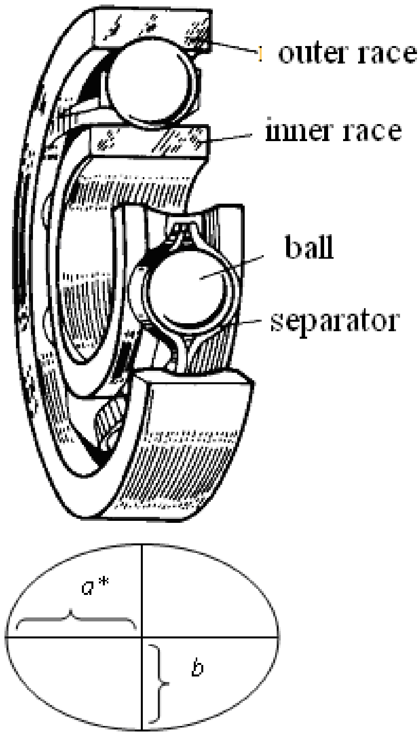

FIGURE 1. THE ROLLING-CONTACT BEARING. THE CONTACT SQUARE IN THE FORM OF AN ELLIPSE WITH SEMIAXIS A* AND B

The contact point radius of the ball with a plane a* is defined by value of loading, mechanical properties of solids and their geometrical sizes and estimates from relationships for an elastic deformation of solids (1):

$$a^* = 1{,}11(NR/E)^{1/3} \quad (1)$$

Where N is a loading, R, E is an effective radius and an elastic modulus, accordingly. An effective radius R is calculated by the formula [9]:

$$\frac{1}{R} = \frac{1}{R_1} \pm \frac{1}{R_2} \quad (2)$$

where R_1 and R_2 are radii of contacting solids, a sign plus (+) is taken at the contact of convex solids, and a sign minus (-) is taken at the contact of the cylinder and a matching cylindrical groove. As races and balls are made of the same material (steel ШХ-15 or its analogue is most often used) the effective modulus is equal to the steel elastic modulus $2.6 \cdot 10^{11}$ Pa. The counted effective radius R for an outer and inner races makes accordingly $3.3 \cdot 10^{-3}$ and $2.8 \cdot 10^{-3}$ m. Calculated radii values of the contact point (a*) depending on loading (N) for the diagram ball-plane are given in the table 1, where P is a medium contact pressure.

TABLE 1
CALCULATED RADIUS VALUES OF CONTACT POINT (*a), MEDIUM CONTACT PRESSURE (P), CONTRACTION RESISTANCE (R_s), OXIDE FILM (R_{ox}) AND GENERAL (R).**

N, H	*a** , 10^{-6}, m	*S*, 10^{-12}, m^2	*P*, GPa	R_s, mOm	R_{ox}, mOm	*R*, mOm
20	74.90	17 615	1.1	2.0	56.8	58.8
100	128.10	51 526	1.9	1.2	19.4	19.6
200	161.30	81 696	2.5	0.9	12.2	13.1
400	203.30	129 779	3.1	0.74	7.7	8.4
600	232.70	170 029	3.5	0.64	5.9	6.5
800	256.10	205 944	3.9	0.58	4.9	5.5
1000	275.80	238 846	4.2	0.54	4.2	4.7
1200	293.10	270 118	4.4	0.51	3.7	4.2
1400	308.50	298 841	4.7	0.49	3.3	3.8
1600	322.60	326 782	4.9	0.47	3.1	3.6
1800	335.45	353 387	5.1	0.45	2.8	3.3
2000	347.40	378 956	5.3	0.43	2.6	3.0

Let's note, that the results given in the table 2, have an approximate character, that is connected on the one part with an experimental estimation of imprint lengths, and on another part it is connected with using of Hertz theory relationships where ideal smooth surfaces are observed, without the account of conjugate solids roughness, in our case of races and bearing balls.

TABLE 2
CALCULATED VALUES OF PARAMETERS FOR ROLLING-CONTACT BEARINGS

N, H	*a*, 10^{-6}, m	*a**,10^{-6}, m	b_{inner} 10^{-6}, m	b_{outer} 10^{-6}, m	S_{inner} 10^{-12}, m^2	S_{outer} 10^{-12}, m^2	P_{inner}, ГPa	P_{outer}, ГPa	R_s, mOm	R_{ox}, mOm	*R*, mOm
20	74,90	299,6	69,4	70,0	65288	65852	0,31	0,30	1,0	30,5	31,5
100	128,10	512,4	113,8	120,2	183097	193394	0,55	0,50	0,6	10,70	10,3
200	161,30	645,2	143,3	151,4	290316	306726	0,69	0,65	0,4	6,70	7,1
400	203,30	813,2	180,5	190,7	460897	486943	0,90	0,80	0,36	4,30	4,7
600	232,70	930,8	206,6	218,2	603832	637736	1,00	0,94	0,32	2,27	3,6
800	256,10	1024,4	227,4	240,2	731459	772631	1,10	1,00	0,30	2,69	2,95
1000	275,80	1103,2	244,9	258,7	848345	896149	1,20	1,10	0,28	1,32	2,64
1200	293,10	1172,4	260,3	274,9	958252	1011999	1,25	1,20	0,26	2,00	2,2
1400	308,50	1234	274	289,4	1061684	1121355	1,30	1,25	0,24	1,84	2,1
1600	322,60	1290,4	286,4	302,5	1160452	1225686	1,40	1,30	0,24	1,66	1,9
1800	335,45	1341,8	298	314,6	1255549	1325489	1,43	1,36	0,22	1,55	1,8
2000	347,4	1389,6	308,5	325,9	1346092	1422014	1,5	1,4	0,22	1,44	1,65
Indexes «inner». «outer» are matched to the values, received for internal and outer races accordingly.											

Result calculations, given in the table 2, coincide with values of contact pressure received in working process [2].

Registered contact resistance value (R_c) achievement to some critical value R_{cr}, means BLL destruction and decreasing R_c to value, characteristic for the "dry" bearing, measured in the version one by experimental way and calculated in the version two (see table 2).

We have offered the new basic scheme (fig. 2) to define tribotechnological properties of BLL which allows to carry out voltage drop measurement in the bearing directly at its operation [3].

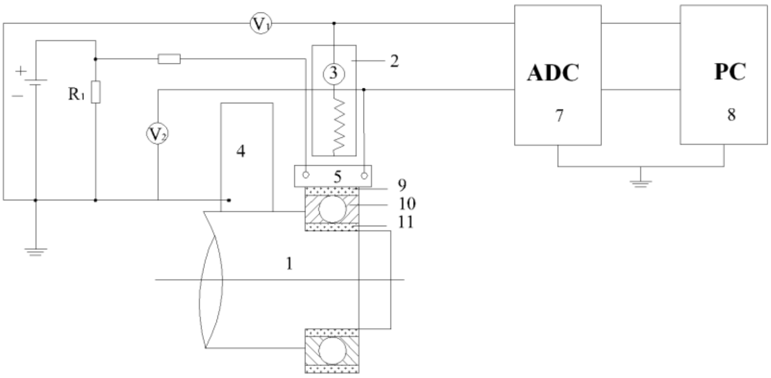

FIGURE 2. THE BLOCK SCHEME (DIRECT) OF THE DEVICE FOR ROLLING-CONTACT BEARING DIAGNOSTIC: 1 - SHAFT; 2 - LOADING UNIT; 3 - LOAD CELL; 4 - FIRST CURRENT COLLECTOR; 5 - SECOND CURRENT COLLECTOR; 6 - CONSTANT-CURRENT SOURCE; 7 - ANALOG-DIGITAL CONVERTER (ADC); 8 - PERSONAL COMPUTER; 9 - INNER (OUTER) RACE; 10 - LUBRICANT; 11 - INNER RACE; R_1 - RESISTANCE; R_2 - CALIBRATING RESISTANCE.

The bearing of the USA manufacture 6202-2RS d16 C3 (Perfect fit industries, inc. Florida, U.S.A.) was used as the second bearing. External diameter of a race is 35 mm. An inner diameter of a race is 16 mm. Balls number is 8 pieces Ball diameter is 4 mm. Width of races is 11 mm.

We have offered the new basic diagram to define tribotechnological properties which allows to carry out voltage drop measurement in the bearing directly at its operation in full-sized unit [3]. The test bench is realized on the basis of the produced friction test machine SMT. Speed makes ≈ 0.5 m/s. Resource test "dry" (without lubricant) bearings were carried out at the maximum radial load ≈ 2000 N [10]. Electronic microscopic pictures and qualitative and also quantitative analysis of element composition of race surfaces was carried out in SC “BELMICROANALYSIS”. Electronic microscopic pictures are gained on transmission electron microscope H-800 (Hitachi, Japan). AFM surface images are gained with using scanning probing microscope NT-206 manufactured by ODO “Microtestmachines”.

III. RESULTS AND DISCUSSION

The schedule of contact resistance (R_c) dependence from time (fig. 3) for two bearings at loading 2000 N is various. The surface of races, manufactured by Slovakia, passes following stages: steams adsorption of solvent elements moisture accompanied by insignificant increasing of R_c level; destruction of adsorbed steams and oxide film to level, characteristic for contraction resistance; intensive surface oxidation with change of chemical compound and structure of oxide film with γ-Fe_2O_3 (white colour) on α-Fe_2O_3 and Fe_3O_4 [10]; elastic energy accumulation in the subsurface layer and formation developed dislocation structure, accompanied by an union of microcracks in macrocracks and sliding strips; the selective mechanism of surface deterioration, proceeding by means of great material volumes separating in the form of petals and a juvenile surface revealing, that leads to level R_c decreasing to the contraction resistance level, wedging of the bearing [12].

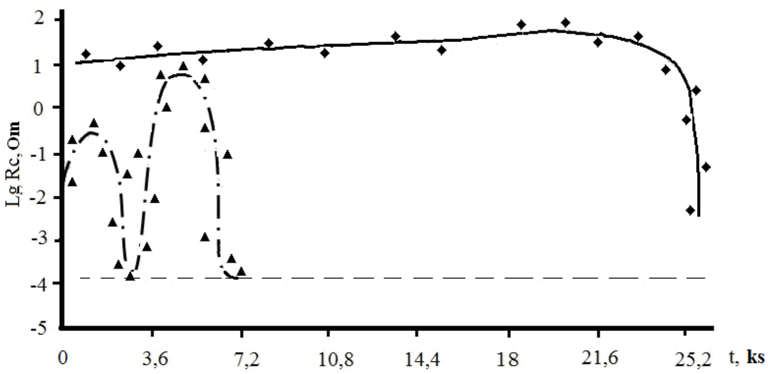

FIGURE 3. THE DEPENDENCE OF CONTACT RESISTANCE (RC) FROM TIME FOR "DRY" BEARINGS AT LOADING 2000 N: ▲ ZVL 6302/16 AND ◆ 6202-2RS D16 C3. A CALCULATED CONTRACTION RESISTANCE VALUE FOR LOADING 2000 N IS SHOWN BY A DOTTED LINE (— —).

We can assume the following bearing process technology 6202-2RS d16 C3. It is known, that the less grain size, the above steel strength and back-to-back endurance. The initial microstructure of bearing steel, characteristic for fine-grained pearlite is represented on fig. 4, arrow 3, reinforced layer (≈ 20 microns) arrow 1 and transitive structure, arrow 2.

High hardness on the surface provides low propensity to scuffing; high fatigue limit; high cavitations durability and good resistance to corrosion in atmosphere. Besides the reinforced layer is well ground and polished, about what the electronic microscopic picture of race surface (fig. 4,) and parameters analysis of surface roughness with using AFM (fig. 5) testifies.

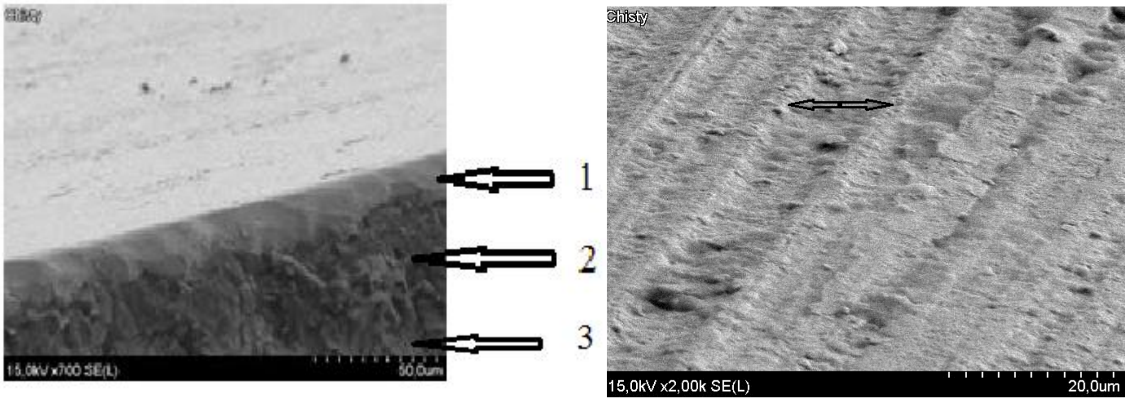

FIGURE 4: A AND B. ELECTRONIC MICROSCOPIC PICTURE: A - RACE CLEAVAGE; B - TOOL MARKS ON RACE SURFACE 6202-2RS D16 C3.

On the electronic microscopic picture of the race surface we can observe clearly visible characteristic parallel each other tool marks along rolling paths on treated surface (fig. 4, b). The distance between them makes ≈ 8-12 microns (fig. 4, b, arrows).

It is known, that the above a roughness class of inner race surfaces, the less is mechanical component of friction factor and therefore is more long a resource of bearing work [1-2]. Analysis AFM of the outer race surface image (fig. 5) shows, that the maximum heights spread (R_q) makes ≈ 2.8 microns.

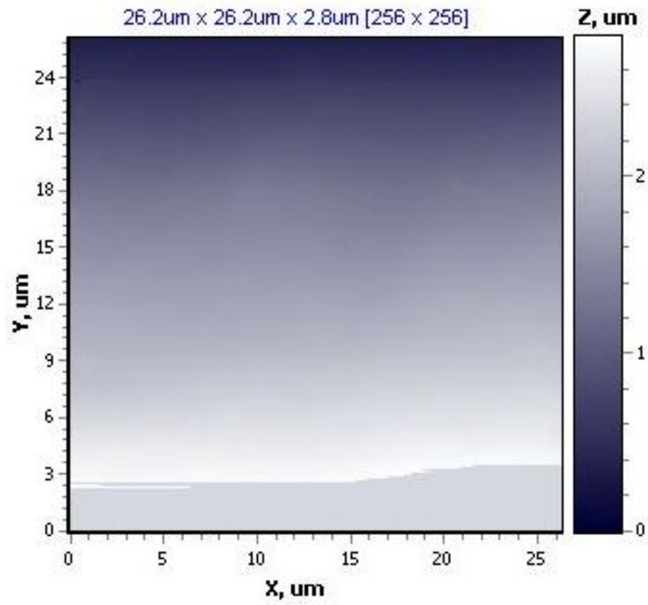

FIGURE 5. AFM THE INNER SURFACE IMAGE OF THE OUTER RACE 6202-2RS D16 C3.

The multicyclic radial bearing loading (2000 N) 6202-2RS d16 C3 leads to microcracks formation on races surface which will increase in sizes, to unit and form macrocracks. As a result of wear fragments separation pits, and hollows are formed on the surface, i.e. the pitting is observed [1-2]. The mechanical component of friction factor increases, that leads to an unimportant increasing of friction factor on a time section t = 11 - 16 ks (fig. 6).

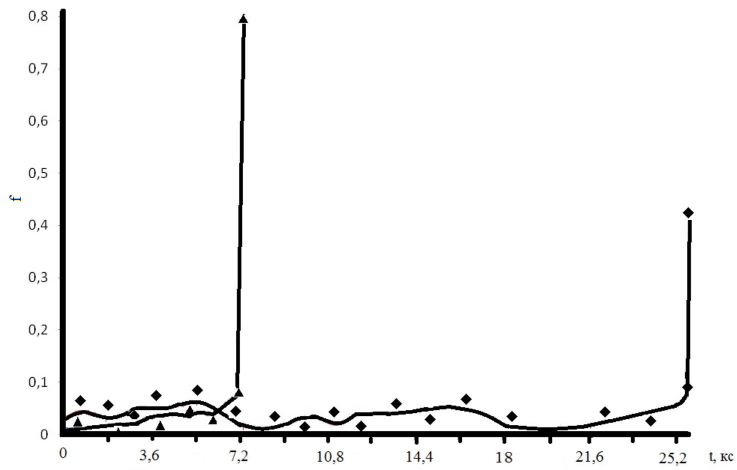

FIGURE 6. DEPENDENCE OF FRICTION FACTOR (F) FROM TIME (T) AT LOADING 2000 N FOR "DRY" BEARINGS: ▲ ZVL 6302/16 AND ◆ 6202-2RS D16 C3.

Sharp temperature drop and friction factor (fig. 6) at time of order 20 ks it is possible to explain by destruction of first mechanically strong coating layer. It is obvious, that heat conductivity of the second layer is above, than at first layer that has led to substantial growth of the heat removal and as consequence to temperature decreasing ≈ 50^o C. This layer does not possess high strength properties that lead to its destruction and increasing of friction factor and temperature. The adhesive and mechanical component of friction factor monotonously increases. Losses for displacement between molecules of a lubricant layer increase that leads to monotonous increasing of temperature. It is observe bearing wedging at t = 25.2 ks, accompanied by sharp increasing of friction factor. It is necessary to note, that to reduce bearing 6202-2RS d16 C3 test time speed of its turning (in terms of linear speed from 0.5 m/s to 1.5 m/s) has been increased three times.

Bearing 6202-2RS d16 C3 operating modes differ from operating modes of bearing ZVL 6302/16. The first stage is characterised by elastic energy accumulation in the subsurface layer and formation developed dislocation structure, accompanied by an union of microcracks in macrocracks and a sliding

strip, at that contact resistance level increases monotonously, that can be caused of simultaneously proceeding surface oxidation process (fig. 3). The level R_c decreasing, but not to contraction resistance level (fig. 3) with simultaneous friction factor increasing at bearing wedging to 0.45, instead of to 0.8 (fig. 6) testify that steel surface destruction (the second stage) proceeds, but not so intensively, as at the selective wearing mechanism as the metal juvenile surface is not revealing (the contraction resistance level will not attain and the friction factor is well below, than for the bearing ZVL 6302/16). At the juvenile surface revealing the adhesive component of friction factor is considerably above for account of conjugate surfaces. The third stage is the bearing wedging.

Thus, the bearing 6202-2RS d16 C3 work resource is six times above in comparison with the bearing ZVL 6302/16, that testifies about dominant role of method and thermal treatment of friction surfaces taking into account constructional features.

IV. CONCLUSION

The substantiation of electrophysical probing methods using for an estimation of operational properties rolling-contact bearings on a condition of the steel bearing surface is given. Electric circuits and techniques are developed. With using of Hertz theory relationships a calculation of contact pressures in system ball races is executed. Dependence of contraction resistance and oxide film on medium contact pressure is installed. On the basis of model surface boundary, estimation techniques of rolling-contact bearings condition control are developed.

Operating modes of rolling-contact bearings depending on steel surfacing process technology are defined. Following condition stages of rolling-contact bearings are installed: formation monomolecular and polymolecular chemisorbed lubricant layers on races; a dynamic equilibrium condition between formation and wearing of lubricant layers; destruction of layers and predominance of the "dry" not greased contacting mode, intensive oxidation of conjugate surfaces and accumulation of elastic energy mode; surfaces wearing mode, mode of intensive selective surfaces wearing; bearing wedging. Definite form of contact resistance dependence, friction factor and temperature are suitable to each stage or a bearing state. So, contact resistance decreasing to level characteristic for the initial "dry" bearing, in each case depending on a surface treatment method it accepts specific value (or a definite values range), for example, for the bearing type ZVL 6302/16 ≈ 0.2-0.5 Om means fracture initiation of monomolecular BLL, and decreasing to ≈ 1 mOm means the beginning of intensive oxidation, dispersing, formation of developed dislocation structure, leading to time local intensive surface wearing and wedging of the rolling-contact bearing. Determination of these criterion values allows at an early stage, before initiation of bearing destruction critical behavior modes, to carry out its condition control at operation. The given criterion can be used at rolling-contact bearings diagnostic. The recommendation to replace lubricant or machines and mechanisms operating modes restriction can be these diagnostic method results, to prevent their catastrophic destruction.

REFERENCES

[1] V.I.Anurev, Handbook of the designer-mechanician, V.2, M.: Mashinostroenie, 2001, 912 p.

[2] M.A.Galahov,A.N.Burmistrov, Calculation of bearing units, M.: Mashinostroenie, 1988, 272 p.

[3] S.V.Korotkevich, V.G.Pinchuk, S.O.Bobovich, Wear resistance of metals at boundary friction, Gomel, Gomel State University of F. Skoriny, 2011, 237 p.

[4] D.Fritzson, J.Stahl and G.Morales-Espejel, Simulation of fretting fatigue in conformal and concentrated contacts, "World Tribology Congress 2009", Kyoto, 6-11 september, 2009, Japanese Society of Tribologists Science Council of Japan, Japan, P. 598.

[5] V.G.Pinchuk, S.V.Korotkevich, Kinetics of hardening and destruction of a surface of metals at friction, LAP Lambert Academic Publishing, 2012, 416 p.

[6] V.G.Pinchuk and S.V.Korotkevich, Microstructure evolution in friction-loaded layers of nickel, Indian Journal of Research,Vol. № 4, Issue № 2, 2015, p. 8-10.

[7] V.G.Pinchuk, S.V.Korotkevich, Physical patterns of dislocation structure kinetics in friction loaded surface layers, Global Journal For Research Analysis, Vol. № 4, Issue № 5, 2015, p. 255-257.

[8] V.G.Pinchuk, I.A.Buyanovskiy and S.V.Korotkevich, Kinetics of Microstructure and Selective Mechanism of Fracture of Metal Surface Layer under Friction, Inorganic Materials: Applied Research, 2015, Vol. № 6, № 5, p. 355-359.

[9] N.K.Myshkin, M.I.Petrokovets, Tribology basics and applications, Gomel: MPRI NASB, 2002, 304 p.

[10] A.A.Djuzhev, S.V.Korotkevich, N.F.Solovej, O.V.Holodilov, Analysis of tribotechnical characteristics of engine oils boundary lubricating layers "Balttrib 2009", Kaunas, 19-21 november, 2009, Aleksandras Stulginskis University, Lithuanian, P. 52-58.

[11] S.V.Korotkevich, A.M.Dubravin, S.M.Martinenko, Influence of the chemical composition and structure of oxidic films on their tribotechnical properties, Friction and wear, V. 21, 2000, № 5, p. 518 – 526.

[12] R.Holm, Electrical Contacts (Russian translation), Moscow, 1961, 464 p.