Increasing the Wear Resistance of the Friction Surfaces of Rotating Parts Made of Bearing Steels Through Hardening Processing Methods

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Abstract. During the study, it was found that the basic technological processes of forming cylindrical working surfaces of friction pairs do not fully provide a rational combination of micro geometric characteristics and physical and mechanical properties of the surface layer. Therefore, we proposed to evaluate the wear resistance of the working surfaces of parts to use a complex indicator that takes into account the influence of technological factors on the properties of the material and the performance characteristics of the surface layer for the running-in and continuous operation modes. Plots of distribution of equivalent stresses by indentors of different geometric configurations are constructed and the optimal shape and material of the deforming element are established. A model of the dynamics of the deformation of the workpiece with a single-axis elastic tool has been developed, which can be used to calculate the radial force in the contact zone. The calculation scheme corresponds to the scheme of the axial cam mechanism. Based on the analysis of the influence of the geometric characteristics of the deforming element on the parameters of the deformation process, a barrel-type indenter was developed for fixing which a slider-type holder was developed with the ability to adjust the stiffness of the dynamic system.

1. Introduction
During the period when the bearing is applied, there is intense local wear of the working surfaces of its parts. Touching surfaces tend to acquire a geometric shape and roughness that will best meet the specific operating conditions [1]. During this process, there are increased contact stresses, which causes thermal processes in the surface layer of the metal, and a decrease in its physical and mechanical properties. In places where the metal surface layer is most deformed, contact stresses increase to critical values [2]. However, if the optimal operational microgeometry of the profile and physical and mechanical properties of the surface layer is provided during the rolling surface shaping, the run-in period will be reduced and the moment of their acquisition of a stable operational state will be accelerated [3]. Basic technologies for forming the working surfaces of bearing rings do not fully provide a rational combination of micro geometric characteristics and physical and mechanical properties of the surface layer. Analysis of manufacturing defects of functional surfaces showed that finishing technologies do not provide the required quality of their manufacture at a sufficient level, which reduces the wear resistance of the roller bearing as a whole [4]. Significantly greater opportunities in technological quality management of surface layers appear during the application of strengthening by smoothing processing methods based on surface plastic deformation (SPD), due to the appearance of favourable technological factors [4,5]. Qualitative and quantitative evaluation of
interaction methods of shaping surfaces of rotation details and operational requirements to the surfaces of rotation of the rings, served as a basis to model the relationships of structural and technological factors, technological operations-enhancing processing performance [6].

To assess the wear resistance of the working surfaces of the rings, we used a complex indicator, $J$, the wear intensity, which takes into account the influence of technological factors on the material properties and operational characteristics of the rings, and derived dependencies for the run-in mode:

$$J_p = \frac{1.2Ra^2}{n\lambda Sm t_p^2} \left( \frac{p}{H\mu_0} \right)^{\frac{7}{6}} \sqrt{15\pi (2\pi Wz H_{max})^{\frac{1}{3}} \left[ 1 + \frac{2\pi H\mu_0 (1 - \mu^2)}{E} \right]}$$

and set operating mode:

$$J_p = \frac{1.2\pi p^{\frac{7}{6}}}{n\lambda t_p^{\frac{3}{2}} H\mu_0^2 \sqrt{30(1 - \mu^2) \cdot (2\pi Ra Wz H\mu_{max})^{\frac{1}{3}}} \sqrt{E \cdot Sm}}$$

where $Ra$ – the arithmetical mean deviation of roughness profile of the surface; $n$ – is the number of cycles which leads to manifestations destruction of the material; $\lambda$ – coefficient taking into account influence of surface residual stresses on the process of wear; $Sm$ is the average pitch of the irregularities of roughness profile; $t_p$ – relative length of the reference line of the roughness profile; $p$ – the working pressure at the contact surface; $H\mu_0$ – surface microhardness; $Wz$ – wave height; $H_{max}$ – maximum height of macro deviations; $\mu$ and $E$ are Poisson's ratio and the modulus of elasticity of the material of the part. The analysis of theoretical and empirical dependences of the operational properties of roller bearing parts showed that they depend on the system of parameters of the quality of functional surfaces: macro deviations – $H_{max}$, $Hp$; undulations – $Wz$, $Wp$, $Smw$; roughness – $Ra$, $Rz$, $R_{max}$, $Rp$, $Sm$, $t_p$; roughness – $Ra'$, $Sm'$; physical and mechanical properties – $\sigma_0$ (surface residual stresses); $h\sigma_0$ (depth of surface residual stresses); $h\mu_0$, $h_l$ (depth of the hardened layer); $l_s$ (grain size); $\rho_d$ (dislocation density).

Elaboration of models of processing by blade, abrasive and smoothing tools allowed to establish sequence of formation of operational parameters in a technological cycle of manufacturing of rings of roller bearings [7–9]. It is found that during processing of the blade formation of roughness depends on the initial roughness $Rz$ and fluctuations in the initial microhardness of the surface layer $H\mu_{max}$, $H\mu_{min}$. The average pitch of the $Sm$ irregularities depends on its initial value, on the $Rz$ and changes in the surface microhardness $H\mu$. Initial macro-deflections are partially inherited during the next machining and depend on the initial physical and mechanical parameters of the surface layer, namely microhardness and depth of residual stress ($H\mu_0$, $h\mu$, $\sigma_0$, $h\sigma_0$). The formation of physical and mechanical properties of the surface layer during machining largely depends on their initial state. Based on the analysis of the influence of the quality parameters of the surface layer with the processing conditions, the hereditary and consequential nature of the relationship between the quality indicators of the surface layer and the performance characteristics is established [10,11].

2. Materials and Methods

The Abbott-Firestone curve of the surface roughness profile is selected for the analysis of performance characteristics. Analysis of different profiles showed that the bearing capacity of the surface layer at a constant height $R(Rz)_{max}$ and the value of $Ra$ is greater, the lower the smoothing height $Rp$ (the distance from the line of protrusions to the middle line). If the values $Rp$ and $R(Rz)_{max}$ are the same, the higher the load-bearing capacity of the surface, the greater the parameter $Ra$. With a decrease in the height of the $R_{max}$ micrometer, the $Ra$ and $Rp$ parameters decrease, and the load-bearing capacity increases. It was found that the load-bearing capacity of surface microcavities depends on the value of the parameter $R(Rz)_{max}$, the smoothing height $Rp$ and the arithmetic mean deviation of the profile.
The optimal shape of the deforming element is determined based on the constructed plots of the equivalent stress distribution (figure 1) by indentors of various geometric configurations and on the basis of the calculations performed, figure 1 (a).

![Figure 1. Changing the equivalent voltage distribution plots depending on the shape of the indenter.](image)

The stress state in the contact zone of the part with the indenter is determined not by the original, but by the plastic deformed shape of its surface as a result of indentation. Considering this, when calculating the stresses arising in the part, not only the initial but also the curvature formed by the plastically deformed surface must be taken into account. In addition, during plastic deformation of the part material, the equivalent stress plot is curved within the deformed layer, reflecting the load history. As the deformation proceeds, the maximum yield point increases and deepens until it reaches the position corresponding to the maximum load. In the process of metal hardening, this result is usually fixed in the cross-section of the surface layer, and the microhardness equalization point determines the limit of the plastically deformed layer, i.e. the depth of strengthening \(h_\sigma\). For the general case of contact of bodies of arbitrary curvature, the main stresses \(\sigma_x, \sigma_y, \sigma_z\), planes perpendicular to the coordinate axes, of which \(z\) is normal to the contact surface, and \(x\) coincides with the main axis of the elliptical contact zone, are defined as:

\[
\sigma_x = -P_y \frac{b}{a} \left[ -\frac{b^2 + z^2}{a^2 + z^2} + \frac{2}{a} (L - K) - 2\mu \left( 1 - \frac{a^2}{b^2} \frac{b^2 + z^2}{a^2 + z^2} + \frac{z}{a} \frac{a^2}{b^2} - K\right) \right] \right] \right] \right] \right] \right] \right] \right] \right]\]

\[
\sigma_y = -P_y \frac{b}{a} \left[ -\frac{b^2 + z^2}{a^2 + z^2} + \frac{2}{a} (L - K) - 1 + 2\mu \left( 1 - \frac{b^2 + z^2}{a^2 + z^2} + \frac{z}{a} (L - K) \right) \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \right] \Righta. The optimal shape of the deforming element is determined based on the constructed plots of the equivalent stress distribution (figure 1) by indentors of various geometric configurations and on the basis of the calculations performed, figure 1 (a).
coefficients $\mu$ and elliptic integrals of the first kind, $K(\epsilon, \theta) = \int_0^\theta \frac{d\theta}{\sqrt{1 - \epsilon^2 \sin^2 \theta}}$, and the second kind, $L(\epsilon, \theta) = \int_0^\theta \sqrt{1 - \epsilon^2 \sin^2 \theta} d\theta$, depending on the parameter and eccentricity of the ellipse, $\epsilon = \sqrt{1 - (b/a)^2}$. For 100Cr6 steel coefficient $\mu = 0.3$, hence it is possible to determine for a number of values $b/a$ and $z_b$ the main Eqs. (3) and equivalent voltage (4):

$$\sigma_{equ} = \sqrt{\left[ (\sigma_x - \sigma_y)^2 + (\sigma_y - \sigma_z)^2 + (\sigma_z - \sigma_x)^2 \right]}.$$  (4)

After equating, according to the Huber-Mises condition, the average tangent stresses $\sigma_{equ}$ to the yield point of the part material in the initial state, the coordinate $z = h \cdot \sigma$ of the boundary of the plastically deformed layer is found.

$$\sigma_{equ} = \frac{3}{2} \frac{P_y}{nab} \sqrt{\frac{1}{2p_y^3} \left[ (\sigma_x - \sigma_y)^2 + (\sigma_y - \sigma_z)^2 + (\sigma_z - \sigma_x)^2 \right].}$$  (5)

3. Results
A model of the dynamics of deformation of the workpiece with a single-indenter elastic tool allows determining the radial force $P_y$ in the contact zone “surface-indenter”. Design scheme (figure 2) corresponds to the axial Cam mechanism, where 1 – Body, 2 – Movable slider with the Indenter 3 is pressed against the Workpiece 5 by a Spring 4 with a stiffness, with the force $P_{y0} = Q_0 = cY_0$ thanks to the Nut 6. Nominal cross-section of the workpiece has the shape of a circle 7 with radius $\rho_0$. The actual section of the billet is represented as a wavy curve that has a maximum height of $W_{max}$, the angular pitch of the wave $\phi_s$, and the Nominal Section Profile 7 is the mean line $m_w$ of the Billet 8, which determines the actual radius of the billet $\rho(\phi)$.

**Figure 2.** Calculation scheme of the process of combined smoothing of rotation surfaces that have deviations from roundness.
1 – Body, 2 – Movable slider, 3 – Indenter, 4 – Spring, 5 – Workpiece, 6 – Nut, 7 – Nominal Cross-section Profile, 8 – Billet.

In the design scheme provided by the following forces: $P_{y0} = Q_0 = cY_0$ – the nominal value of the smoothing force; $P_y = Q$ – the resulting impact force of the indenter on the surface in the contact zone; $m\ddot{y}$ – the inertial force of moving parts of the tool; $\ddot{P}_y$ – the reaction force of the workpiece on the indenter; $\bar{P}_z$ – strength of resistance to smoothing; $\ddot{P}$ – resultant force smoothing; $m\ddot{y}$ – the
weight of the moving parts of the tool; \( \bar{N}_1, \bar{N}_2 \) the force reactions in the bearings of the slider; \( \bar{F}_1, \bar{F}_2 \) – the friction force-sliding that occurs during the movement of the slider; \( \eta \bar{Y} \) – the moment of resistance proportional to the speed of movement of the slider caused by the presence of lubricating and cooling fluid (coolant).

A number of issues have been solved using mathematical modelling:

• The necessary conditions for ensuring stable contact of the indenter and the workpiece are determined, that is, the possibility of separation of the indenter and the occurrence of impact of the indenter on the surface of the workpiece is excluded:

\[
f(\omega t) = f(\phi) = \rho
\]  

(6)

• The range of smoothing speeds \((v_{min}, v_{max})\) is defined, within which the smoothing force \(Q\) will be stored in the allowed range \((Q_{max_{min}})\), which must be maintained in order to form the quality parameters of the surface layer with regulated reliability:

\[
Q_0 - \Delta Q \leq Q_0 + cf(\omega t) + M\omega^2 f''(\omega t) \leq Q_0 + \Delta Q
\]  

(7)

• A number of additional operating conditions of the tool are determined in order to select the optimal technological modes of processing, namely: slider acceleration,

\[
y''(t) = \omega^2 f''(\phi) = \omega^2 f''(\omega t)
\]  

(8)

• Slider jamming condition

\[
tg\gamma_{jc} = \frac{1}{f(1 + \frac{2h}{L})}
\]  

(9)

• Equation of forced vibrations

\[
y' + 2nY + \omega_0^2 Y = \frac{cf(t)}{m}
\]  

(10)

• The coefficient of dynamic

\[
\mu = \frac{a}{Y_{st}} = \frac{1}{\sqrt{\left(1 - \frac{\omega^2}{\omega_0^2}\right) + \frac{4\omega^2n^2}{\omega_0^4}}}
\]  

(11)

• Oscillation amplitude

\[
a = \frac{Y_{st}}{\sqrt{\left(1 - \frac{\omega^2}{\omega_0^2}\right) + \left(\frac{k\alpha^{n-1}}{c}\right)^2}}
\]  

(12)

Based on the analysis of the geometric characteristics of the deforming element on the parameters of the deformation process for the developed tool (figure 3), a barrel-type indenter made of a hard alloy MC241 was made. To fix the deforming body, a slider-type assembly was developed consisting of: the Housing 1, the Adjusting Washer 2, the Cover 3, three Screws 4, and the Indenter 5. In this node, a groove is cut in order to ensure that it is accurately based relative to the workpiece, with the ability to move relative to the tool axis. The housing 1 has an elliptical recess in which the indenter 5 can perform rotational movements around its axis. The washer 2 is designed to regulate the accuracy of fixing the indenter since after a while there are wear in the housing 1, which can be eliminated by replacing it. Cover 3 secures the indenter in the node. Housing, adjustment washer, and the lid made of heat-resistant material CuZn37Al1-C.
Figure 3. Consolidation of the indenter and the main structural elements of the holder. 
1 – Housing, 2 – Adjusting washer, 3 – Cover 3, 4 – Screws, 5 – Indenter 5, 
6 – Spring 7 – Nut, 8 – Guide, 9 – Holder, 10 – Scale, 11 – Screw.

The preload is created by compressing the Spring 6 with the Nut 7. To determine the preload force
$P_{y0}$, a Scale 10 is applied to the Holder 9. The slider in the holder 9 is placed along with the guide 8.
The holder 9 has a hole where the inductive Converter model 221 is mounted and secured with a Screw 11.
Measurements of the smoothing force active control of the process of smoothing the rolling
surfaces of the rings were carried out using a sensor, the signal from which was transmitted to the primary converter, and later the signal was transmitted in a unified form to the analogue-to-digital converter “L-Card E-154” and a PC.

Figure 4. Analysis of microgeometric parameters of functional surfaces using
Mountains Map Universal software.

4. Discussion
Experimental studies of the influence of surface layer quality parameters on the wear resistance of the
working surfaces of roller bearing rings during strengthening and smoothing operations have been
conducted. The influence of the smoothing force $P_y$ on the depth, width, height of inflows, and the
area of irregularities in the cross-section was determined by the method of test passes. Fragments of
the studied surfaces and their indicators are shown in figure 4. The study of the surface microgeometry was carried out using the Rank Taylor Hobson Talyskan 150.
Study of parameters of quality of surfaces of rolling operations carried out by SPD regressing multi-factor model reflecting a quantitative relationship between radial force smoothing $P_y$, feed $S$, spindle speed $n$, source parameters of surface layer quality $Ra_{in}$ (arithmetical mean deviation of the profile, source) $Sm_{in}$ (the average step roughness profile, baseline) and quality parameters of the surface layer ($Ra$, $Sm$, $H\mu$), on the basis of the developed experimental setup.

The influence of technological factors on the geometric parameters of the microrelief and wear resistance was studied on samples made of steel 100Cr6 in accordance with the developed methodology. These samples were roughed, the hardness is 55-60 HRC, the initial surface roughness is equal to $Ra_{in} = 0.5-0.7$ microns.

The influence of technological factors (smoothing forces $P_y$, the radius of the deforming element $R_d$, tool feed $S$, speed of rotation of the spindle $n$) on the geometric parameters of the microrelief (depth $h_s$, width $b$, the height of swells $h_{sw}$, relative reference area $t_p$, the average pitch of profile irregularities $Sm$, arithmetic mean deviation of the profile $Ra$) and physical and mechanical properties of the surface layer (surface microhardness $H\mu$) was studied. Based on the results of experimental studies and mathematical modeling, empirical dependencies are obtained (13), (14), (15) parameters of the surface layer after combined smoothing from the modes $P_y$, $S$, $n$ for strengthening and smoothing operation using a single-tool elastic action tool.

$$Ra = 2.761 \cdot 0.00225 \cdot P_y + 7.01 \cdot S - 0.0184 \cdot n - 1.255 \cdot Ra_{in} - 0.0415 \cdot Sm -$$
$$-0.000009 \cdot P_y \cdot n + 0.00676 \cdot P_y \cdot Ra_{in} + 0.00018 \cdot P_y \cdot Sm + 0.0277 \cdot S \cdot n - 0.178 \cdot S \cdot Sm$$  \hspace{1cm} (13)
$$+0.00744 \cdot Ra_{in} \cdot n + 0.000143 \cdot n \cdot Sm + 0.01492 \cdot Ra_{in} \cdot Sm + 0.59 \cdot P_y \cdot S$$

$$Sm = -116.7 + 0.032 \cdot P_y - 106 \cdot S \cdot n + (-0.275 \cdot n) + 35.5 \cdot Ra_{in} +$$
$$+5.787 \cdot Sm_{in} - 0.00069 \cdot P_y \cdot n + 429 \cdot S \cdot Ra_{in} - 23.3 \cdot S \cdot Sm_{in} +$$
$$+0.0896 \cdot Ra_{in} \cdot n - 2.118 \cdot Ra_{in} \cdot Sm_{in} + 3.17 \cdot n \cdot S - 0.00245 \cdot n \cdot Sm_{in}$$  \hspace{1cm} (14)

$$H\mu = 3601 + 77.4 \cdot P_y - 3910 \cdot S - 2.04 \cdot n - 11.93 \cdot Ra_{in} - 41 \cdot Sm - 0.019 \cdot P_y \cdot n -$$
$$-1.75 \cdot P_y \cdot Ra_{in} + 10 \cdot 185 \cdot S \cdot Ra_{in} + 100 \cdot S \cdot Sm + 0.032 \cdot n \cdot Sm +$$
$$+16.4 \cdot Ra_{in} \cdot Sm - 626 \cdot P_y \cdot S$$  \hspace{1cm} (15)

On the basis of experimental and theoretical studies, graphical dependencies of microgeometry parameters of the treated surfaces on the parameters of the $P_y$, $S$, $n$, smoothing modes are constructed, which allow optimizing the technological factors of for strengthening and smoothing operation to obtain surfaces with predicted values of microgeometry parameters of the surface layer and improved performance properties.

In order to improve the performance of roller bearing rings and reduce the cost of manufacturing them, it is proposed to redistribute the allowance for grinding operations in the technological cycle of ring manufacturing and replace the superfinishing operation with combined smoothing.

Elaboration of empirical data (13), (14), (15) and graphical dependencies allowed us to establish that reducing $Ra$ by 6 times reduces the intensity of surface wear also by 6 times, reducing $Sm$ by 2.5 times reduces the intensity of surface wear by 4.4 times, increasing $H\mu$ by 5 times increases the wear resistance of the surface by 7.5 times (under all other identical conditions). Therefore, the wear resistance is most affected by the surface microhardness $H\mu$, the arithmetic means deviation of the profile $Ra$ and the average pitch of the irregularities $Sm$.

Studies of the wear process and determination of the burn-in period were performed by the installation VNIPP-542 (figure 5). Tests were performed on new roller bearings. The experiment ended when the bearing began to collapse. This was determined by the period of stable operation of the roller bearing, depending on the method of finishing.
Figure 5. Installation of VNIPP-542 to test the wear resistance of bearings.

As the samples used were roller bearings of the 700 series (steel 100Cr6, hardness HRC 60-62) made according to various finishing technologies, with the microstructure of martensite with carbides. 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\(\mu\)), the remaining 4 samples were made by basic technology – superfinishing with the height of micro-inequalities 0.8\(\mu\); 1.5\(\mu\); 3\(\mu\) and 6\(\mu\). The inner and outer rings had the same roughness.

If the material densities of the reference and test samples are equal may be replaced by the ratio of absolute wear of the mass. It is allowed to list mass demolitions for linear ones, taking into account the density of the sample materials, when it is impossible to accurately measure the absolute linear wear, or when the density of the reference and test samples is different. The relative wear resistance calculated as the arithmetic mean of the results of two identical experiments is taken as the result of testing the material.

Studies of roller bearings treated with strengthening smoothing for wear resistance were carried out under the following conditions: \(F_a=24 \text{ kgf/cm}^2\), \(F_r=14 \text{ kgf/cm}^2\) (axial and radial loads, respectively); \(n =1300 \text{ rpm}\); \(T_{10}=252 \text{ hour}\). It was found that the wear resistance of the rolling surfaces of roller bearing rings increases by 15-20% with the use of hardening and smoothing technologies. The physical picture of the experimental fact of increasing the wear resistance of functional surfaces after hardening smoothing operations confirmed the validity of the theoretical positions.

5. Conclusions
The contact resistance of rolling surface is ensured not only by thermal and chemical-thermal effects, but also methods of a rational combination of grinding and firming-smoothing processing, such as directional influence on the smoothing of the peaks of the asperities of the surface, providing the effect of riveting the surface layer, and as a result of the reduction period, the running contact surfaces by 30 % and increase the resource of work at 10 %.

According to the research results, the technology of combined grinding and hardening-smoothing machining of the rolling surfaces of the rings has been developed, which provides an increased level of wear resistance of roller bearings by 15-20 % and reduces the cost of finishing operations by 12 %. A mathematical model of the process of smoothing with a single-indenter tool of elastic action on the basis of which the radial force in the contact zone "surface - indenter" \(P_y=200 \text{ N}\) is determined.

The conditions for ensuring continuous contact of the indenter from the workpiece for the frequency range of the workpiece \(-400-600 \text{ rpm}\), which is the basis for ensuring the stability of the smoothing process at the stage of technological design.

Based on modeling the dynamics of the smoothing process, taking into account the deformation gradient of the workpiece material, the geometric configuration of the deforming element (indenter) of an ellipsoid type with a profile radius \(R_d=20 \text{ mm}\) and the ratio of the length of the vertical axis \(l_a\) to the horizontal \(l_b = 1+0.63\), respectively, and the design of the tool block with a mechanism for setting and stabilizing the radial smoothing force \(P_y\).
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