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Book Title	Advanced Manufacturing Processes II	
Series Title		
Chapter Title	Influence of Technological Methods of Processing on Wear Resistance of Conjugated Cylindrical Surfaces	
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Abstract

Wear of any tribological pair leads to malfunction or failure of the entire mechanism. It is known that the process of wear of friction pairs occurs in three periods: running-in, normal wear, accelerated wear (destruction). Working surfaces of parts that are formed in the manufacturing process receive micro geometric characteristics (roughness, undulation), according to the regulated technological norms. These characteristics describe the properties of the technological surface topography. However, quantitative micro geometric parameters change as they evolve during running-in, and the surface receives a new operational relief that is stable for a long time during normal wear. It is an operational relief of conjugate surfaces that characterizes the qualitative properties of parts for a long period of operation. The running-in process, which is based on complex mechanical, physical, and chemical processes, determines the overall wear resistance of parts. After this period, the physical, mechanical, and geometric characteristics of the surface acquire optimal values corresponding to the operating conditions. Rational performance characteristics during normal wear can self-sustain, and they are continuously reproduced independently in the same values. This state of the surface layer is observed before the beginning of the third stage of the life cycle. Traditionally, to ensure regulated micro geometric characteristics of the working surfaces used grinding, smoothing, and lapping diamond pastes. At the present stage of development of equipment and technology in a row with the mentioned finishing operations, there is an operation of high-speed turning, which allows reaching high purity of surfaces with the lowest cost of the technological process.

Keywords (separated by '-') Analysis - Micro relief - Running-in - Abbott–firestone curve - Dimensionless complex

Influence of Technological Methods of Processing on Wear Resistance of Conjugated Cylindrical Surfaces

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Abstract. Wear of any tribological pair leads to malfunction or failure of the entire mechanism. It is known that the process of wear of friction pairs occurs in three periods: running-in, normal wear, accelerated wear (destruction). Working surfaces of parts that are formed in the manufacturing process receive micro geometric characteristics (roughness, undulation), according to the regulated technological norms. These characteristics describe the properties of the technological surface topography. However, quantitative micro geometric parameters change as they evolve during running-in, and the surface receives a new operational relief that is stable for a long time during normal wear. It is an operational relief of conjugate surfaces that characterizes the qualitative properties of parts for a long period of operation. The running-in process, which is based on complex mechanical, physical, and chemical processes, determines the overall wear resistance of parts. After this period, the physical, mechanical, and geometric characteristics of the surface acquire optimal values corresponding to the operating conditions. Rational performance characteristics during normal wear can self-sustain, and they are continuously reproduced independently in the same values. This state of the surface layer is observed before the beginning of the third stage of the life cycle. Traditionally, to ensure regulated micro geometric characteristics of the working surfaces used grinding, smoothing, and lapping diamond pastes. At the present stage of development of equipment and technology in a row with the mentioned finishing operations, there is an operation of high-speed turning, which allows reaching high purity of surfaces with the lowest cost of the technological process.

Keywords: Analysis · Micro relief · Running-in · Abbott–firestone curve · Dimensionless complex

1 Introduction

For the effective operation of machines and mechanisms, it is necessary that in the process of machining, the surfaces of parts acquire a set of characteristics that occur during the running-in period [1]. Then the friction pair in the manufacturing process will acquire the properties that are inherent in the conjugate surfaces of lapped parts, minimizing the running-in period [2].

V. Tonkonogyi et al. (Eds.): InterPartner 2020, LNME, pp. 1–11, 2021.
https://doi.org/10.1007/978-3-030-68014-5_47

However, the acquisition of optimal surface characteristics and compensation of deviations in the properties of the treated surfaces, during the operation of the part can take place only within certain limits [3]. Thus, during the study of the inner rings of roller bearings found that the roughness decreases particularly intensively in the first 2 h of operation. After 8 h of operation, the surfaces acquire optimal roughness Ra = 0.08–0.04 μm. High projections microrelief rather reduce its height and lower-slower. It is noted that the surfaces with Ra = 0.08–0.04 μm, which had an initial roughness of Ra = 1.25–0.32 μm, during the operation suddenly acquired a "coarse" surface roughness and re-started proportionately [4]. This phenomenon is explained by the following: in the process of burnishing "rough" output surfaces, the optimum value of roughness is reached due to the plastic flow of the metal, particularly due to the formation of a surface film of the metal. Thus, remain unfilled metal sharp corners of hollows of a microrelief of a surface. During operation (normal wear and tear), the metal layer is destroyed, and the surface with the initial roughness is exposed under it. This phenomenon is harmful because it increases the running-in time and scratches the mating surfaces with metal particles. Thus, it can be noted that rough initial surfaces pass the stage of "false burn-in" [1].

Surfaces with initial roughness Ra = 0.32–0.08 μm have a normal break-in period. Here the optimum roughness value Ra = 0.08 is achieved 0.04 μm in about 1.5 h of operation, and a surface with a roughness close to operational has a short running-in period (about 5 min). Normal running-in is characterized by the fact that under the microrelief, which was formed is a dense, well-filled metal base. Changes in microrelief parameters occur mainly because of abrasion and minor plastic deformation of the vertices. Rolling cavities microrelief surface and subsequent failure of the bulk layer does not occur here.

Thus, with the aim of the study of the formation of the technological surface during running, it is proposed to undertake a study on the character of changes of the working surfaces of mating parts to establish as close machining operation to this process.

2 Literature Review

The period of intensive reduction of roughness coincides with the period of intensive increase in the degree of work hardening and, consequently, the value of micro hardness. By the end of the running-in period, its value is stabilized and takes an optimal value.

In [5, 6], it is shown that the process of burnishing the working surfaces of machine parts is accompanied by a change in the initial technological roughness and micro-hardness obtained after machining and the formation of operational values of these characteristics. However, in papers [7, 8], only the change in the height characteristics of the roughness Ra or Rmax is considered. However, the change in the shape of the micro-irregularities determined by the plane and volume characteristics is insufficiently investigated. This issue is especially important in the study of the influence of technological processing methods on the formation in the process of burnishing the operational microrelief [9–11], as well as for ensuring the accuracy and the optimal configuration of technological systems [12, 13]. During the study, the analysis of changes in the main characteristics of the microgeometry and microhardness of the surface layer during running-in.

3 Research Methodology

The process of stable work of parts, which is based on complex mechanical, physical, and chemical processes, determines its overall wear resistance. Before this process, the physical and geometric characteristics of the surface, such as roughness, microhardness, magnitude and sign of residual stresses, structure metal, friction coefficient, and others, acquire optimum values, respectively, of operating conditions and wear. Optimum performance characteristics during normal wear and tear are supported, evolutionary, and they are continuously reproduced in the same values that are manifested by technological heredity [3].

As the object of study was a pair that operates under boundary friction: $P_d = 0.8$ MPa; $v_d = 0.9$ m/s; oil – 10W-40. The material of mating parts – the 100Cr6 steel (hardness HRC = 58–60). Wear tests were carried out according to the scheme of friction of the liner on the roller that rotates. The roller was processed in a special cartridge to eliminate the manifestations of technological heredity as much as possible [10, 14]. Two series of samples with different hardness and consisting of five samples were investigated. Samples underwent finishing by grinding (v_{ctrl} – 30 m/s; $v_d = 25$ m/min, $s = 0.03$ mm/rev; $t = 0.02$ mm). The change in the profile of the rollers' microroughness during running-in is shown in Fig. 1.

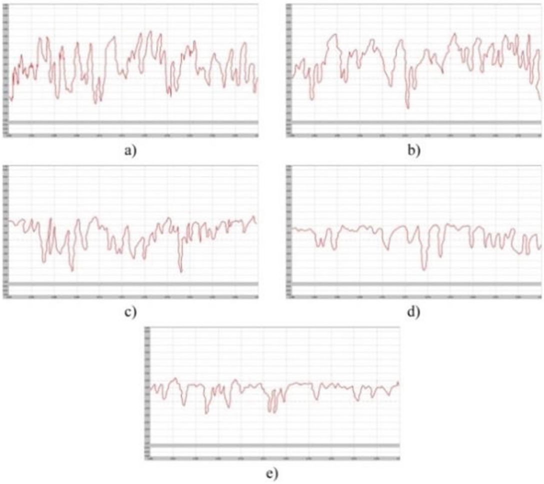


Fig. 1. The changing profile of asperities rollers (steel 100Cr6) during running-in depending on the traversed path friction: a) initial profile; b) $S_T = 0.406$ km; c) $S_T = 0.812$ km; d) $S_T = 1.62$ km; e) $S_T = 2.85$ km.

The profilograms were shot on the same part of the roller surface in the same direction after passing a different friction path S_T.

For Fig. 2 curves of change of average values of roughness characteristics Ra, R_{max}, b', v, r, β in the process of samples wear (HRC = 58) are shown). Obtained after grinding the characteristics of surface quality (Ra = 0.68 µm, R_{max} = 4.2 µm; b' = 1.55 V; v = 1.9; r = 72 µm; β = 9°30′; $N\mu$ = 7900 MPa) during running we observed a decrease of the height irregularities R_{max}. And the main change of R_{max} occurred in the first hours of work. So, within the first hour (S_T = 0.406 km) output height of the irregularities was reduced by 0.32 $R_{max\ int}$, but the next 10 h of operation (S_T = 4.46 km), it has declined by only 0.42$R_{max\ int}$.

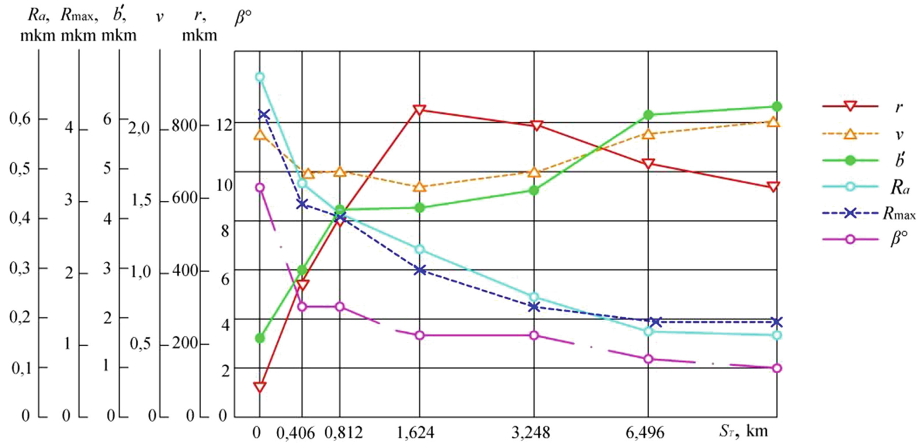


Fig. 2. Characteristics of the roughness for the polished surface in the process of burnishing the roller on the distance traveled.

Similarly, the value of the arithmetic means deviation Ra changes during running-in, which indicates the presence of a relationship between the characteristics of Ra and R_{max}.

Interesting was the change of the radius of curvature of the vertices of the irregularities r. a Sharp increase in the radius to r = 850 µm (S_T = 1.624 km) shows that the removal of the upper part of the microroughness reaches a level at which the inequalities represent the basis of the projections of the initial roughness. In the future, this surface ends with the formation of the working relief. A lower value of r characterizes the last one.

The creation of roughness on the surface with large values of the radius of curvature r can contribute to an accelerated transition to the operational microrelief and reduce the overall value of wear.

The peculiarity of changing the angle of inclination of micro-irregularities β is its rapid stabilization with a total change from 9° to 2°. Thus, during the first two hours of operation (S_T = 0.812 km), there was a 70% change in the angle β.

The most complex changes are the parameters of the curve of the support surface b' and v. The rapid erasure of the individual most prominent irregularities in the first two hours (S_T = 0.812 km) leads to an increase in *b*' more than three times. After the formation of roughness with significant values of the bearing surface area, the value of linear wear, changes in the height of the microroughness, and other characteristics are stabilized, which leads to changes in the following hours of operation of the parameter *b*'. With the further formation of operational roughness ($S_T > 2.85$ km), this parameter is qualitatively different from the initial roughness, i.e., the value of *b*' increases. This is confirmed by the curves of the support surfaces (Fig. 3).

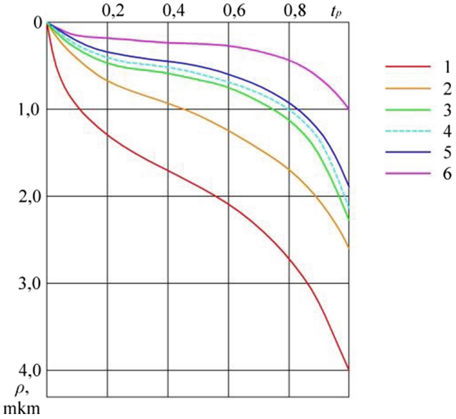


Fig. 3. The dependence of the support surface from the distance *d* after different periods of running rollers made of steel 100Cr6 (HRC = 58–60): 1 – after grinding (S_T = 0 km); 2 – S_T = 0.406 km; 3 – S_T = 0.812 km; 4 – S_T = 1.624 km; 5 – S_T = 2.85 km; 6 – S_T = 4.46 km.

Curves 3–5, corresponding to the friction path 0.812; 1.624; 2.85 km, respectively, are almost identical, changing their shape occurs during the first two hours of operation (S_T = 0.812 km).

The results of a study of changes in the hardening of the surface layer during running, which was carried out on two series of samples of steel 100Cr6 after finishing sanding with the initial microhardness of 7000 MPa (HRC = 51–52) and 7900 MPa (HRC = 58–60), and the corresponding curves are shown in Fig. 4.

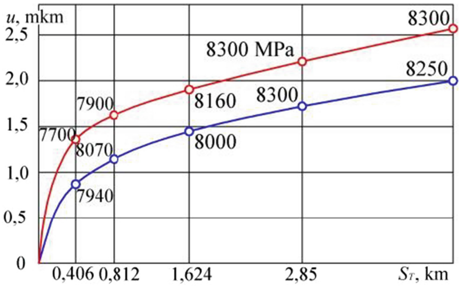


Fig. 4. The dependence of wear and microhardness of the surface of the conjugate surface during running rollers made of steel 100Cr6 from the traversed path of friction.

4 Results

The change in the microhardness of the surface layers in the process of burnishing is determined by the condition of equality of the external load and the yield strength of the metal by the value of the actual reference surface. Due to the small size of the bearing surface at the initial moment of wear occurs plastic deformation of the surface layers, which increases their microhardness ($S_T = 2.85$ km). An increase in the bearing surface further leads to a decrease in the yield strength of the metal, because of which the microhardness in the process of further wear of the previously hardened layer reduces its value.

After the formation of functional roughness, wear occurs without changing its characteristics. This leads to the formation of the optimal microhardness of the surface layer [15–17].

Abbott-Firestone curves (Fig. 3) show that the wear resistance of the samples depends on compliance with all processing conditions. Even minor changes in the technological process lead to an increase in the value of wear by about 25%. This fact indicates the influence of technological heredity on the wear resistance of the studied parts.

From the point of view of technological control of the burnishing process, it is important to know how the processing methods finally form the surface quality, that is, affect the change in the characteristics of the surface layer. With this purpose we studied diamond grinding ($v_{cntr} = 30$ m/s; $v_d = 35$ m/min, $P = 80$ N; $s = 0.15$ mm/rev) diamond lapping pastes, smoothing ($v = 62$ m/min; $s = 0.07$ mm/rev, $P = 1200$ N) and high-speed turning ($v = 200$ m/min; $s = 0.2$ mm/rev; $t = 1.5$ mm).

As in the previous case, a series of five samples were processed and tested for wear by each method. Pre-working the surface of samples of hardened steel 100Cr6 processed round grinding ($v_{cntr} = 30$ m/s; $v_d = 25$ m/min, $S_{pr} = 0.03$ mm/rev; $t = 0.02$ mm).

Change of surface microgeometry characteristics Ra and R_{max}. For samples treated with diamond grinding wheel end, smoothing and high-speed turning (Fig. 5), has a similar character as for round grinding.

According to another algorithm, changes the values of Ra and R_{max} during burnishing for samples treated with lapping diamond pastes. This method obtained roughness with a value of Ra < 0.08 µm, which in its magnitude, is close to the operational roughness. In this regard, it can be argued that the surface will run faster than others, having 2…3 big roughness Ra. It turned out that on the samples ground with diamond pastes, there is an increase in the characteristics Ra and R_{max} to a certain value ($S_T = 1.22$ km), after which there is a decrease in these characteristics to the final values of the operational roughness.

The phenomenon under consideration, similar to the process of false burnishing, in this case, can be explained by different height microgeometry of the sample and counterbody, which was processed by internal grinding ($v_{cntr} = 30$ m/s; $v_d = 30$ m/min, $S_{gr} = 0.02$ mm/rev; $t = 0.01$ mm) with a roughness Ra = 0.63–0,32 µm.

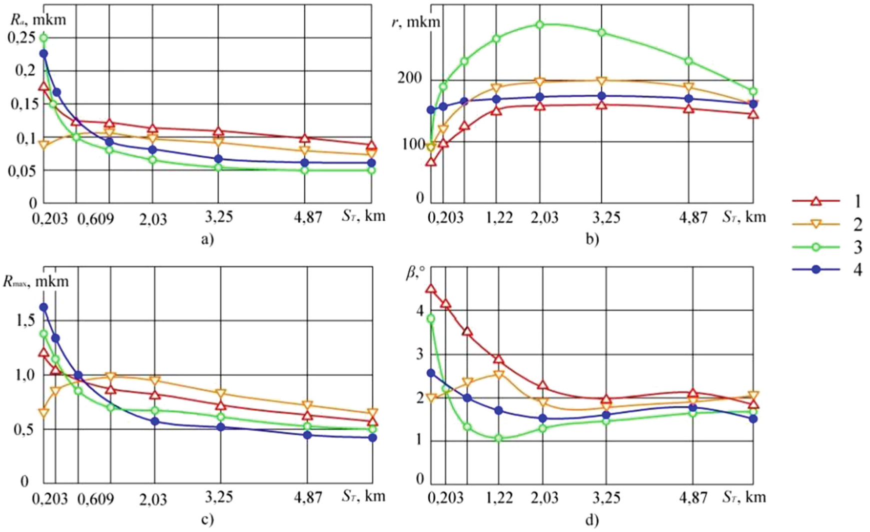


Fig. 5. Dependence of the characteristics Ra (a), *r* (b), R_{max} (c) and β (d) on the friction path for various methods of finishing steel samples 100Cr6: 1 – diamond grinding wheel end; 2 – lapping diamond pastes; 3 – smoothing; 4 – high-speed turning.

On the one hand, the longer the process of burnishing parts of the friction pair with the same hardness, the slower the change in the greatest height of the irregularities for one of the conjugate parts. At the same time, the lower the height of the sample microroughness, the slower the counterbody roughness changes.

On the other hand, roughness value 0.63 of the hardened counterbody interacting with the surface of the sample leads to an increase in the height of the microroughness. The resulting new roughness of the sample leads to faster wear of the counterbody surface and the pair as a whole.

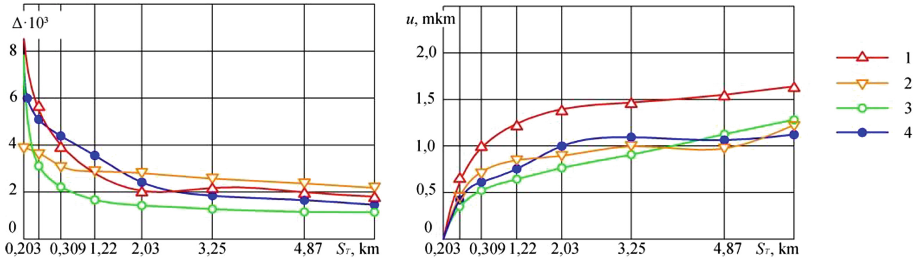
The desire to reduce the amount of wear in the running-in process by obtaining microgeometry, equal only to the height of the operational roughness, both for the sample and the counterbody (processing was carried out by lapping diamond pastes to Ra = 0.08–0.04 µm) led to intense wear by setting. This example proves that obtaining during the treatment of friction surfaces roughness with a height of R_{max} equal to the operational one cannot be a reliable indicator of the optimality of microgeometry, which ensures minimal wear during running-in.

It is obvious that the term "optimal micro geometry" should be understood as the optimal values of all characteristics of microgeometry or complex expression of surface properties that have the maximum impact on wear resistance.

The change in the radius of curvature of the vertices of micro-irregularities for different processing methods during burnishing is shown in Fig. 5b. Similarly, as for round grinding in general, there is an increase in the index r, and then a decrease to a certain value, which characterizes the operational roughness. However, high-speed turning creates a microgeometry in which there is a slight change in r. It can also be assumed that the decrease in microroughness R_{max} (which determines the value of the radii of the protrusions r) leads to a smaller change in the radius of curvature of the irregularities during running-in.

The change in the angle of inclination of the side of the micro-irregularities β in the process of burnishing for different processing methods is shown in Fig. 5d. Changes in the microgeometry of samples lapped with diamond pastes leads to wear in the first hours to an increase in the angle β. A significant increase in the radius of curvature of irregularities r in samples treated with smoothing, to a certain decrease in the values β, smaller than established at the end of the running-in period. As for round grinding, the most complex changes in the running-in process are parameters of the support surface curve b' and v. For example of samples with a minimum value of R_{max} (lapping with diamond pastes), after a slight increase in the value of b', it decreases due to an increase in the height of the micro-roughness due to the influence of the roughness of the counterbody. After burnishing, these surfaces increase in the values of b' (the period of formation of the working relief). From this example, it can be seen that the change in the parameters b' and v depends not only on their magnitude but also on the change in the process of wear for other characteristics of the surface. Thus, more favorable values for the running-in conditions of the radius of curvature of the vertices r, associated angles β, as well as characteristics Ra and R_{max} lead to smaller and more monotonic changes in the parameters b' and v.

An analysis of the data given in Fig. 2–5 allows concluding that regardless of the methods of finishing for all studied characteristics, there is a certain tendency to the formation of working relief in a narrow range, especially for the values of Ra, $R_{max,}$ and angle β. However, when studying the formation of operational roughness, it is more expedient to evaluate complex expressions that include all the main characteristics of the surface microgeometry. As such expression, it is necessary to use the complex dimensionless characteristic of the roughness of a bearing surface $\Delta = R_{max} / r\, b^{I\ 1/\upsilon}$ which is widely applied in settlement dependences for determination of the size of wear [8, 18, 19]. According to the results of the experiment, the values of Δ were calculated. As a result, the dependencies of the change of the dimensionless complex Δ in the process of running-in were built (Fig. 6).



a)

b)

Fig. 6. The dependence of the dimensionless complex Δ (a) and the wear of the samples (b) from the traversed path of friction during running for different methods of finishing processing of samples of steel 100Cr6: 1 – diamond grinding; 2 – lapping with diamond pastes; 3 – smoothing; 4 – high-speed turning.

These dependencies show: despite significant fluctuations in individual characteristics of microgeometry (Fig. 1), there is a certain regularity of monotonic reduction of the Δ complex in the process of burnishing, which is typical for all the studied processing methods.

5 Conclusions

According to the results obtained, it is possible to make an important assumption that the deviation of one of the characteristics from the general pattern should be compensated by a corresponding change in other characteristics included in the dimensionless complex. As a result, the general pattern of change Δ should remain constant for a particular processing method. For example, for samples after lapping diamond smoothing treatment, the increase in the height of the microroughness $R_{\max}$ does not lead to an increase in Δ due to compensating changes in the characteristics of r, b' and v.

The obtained data confirm the correctness of the use of dimensionless complex Δ as the main characteristic of surface microgeometry in the study of friction and wear processes. To predict the change in microgeometry during running-in, an empirical dependencies of the change in the dimensionless complex Δ as a function of the number of wear cycles N or the friction path S_T are obtained.

The equation, which describes the studied dependences, was found with three arbitrary constants and had the form:

$$\Delta = \Delta_{out} - k(1 + \mathrm{e}^{-C \cdot x}), \tag{1}$$

where x – the number of wear cycles N or the friction path S_T, km; Δ_{out} – the value of the dimensionless complex after finishing; C – the coefficient depending on the quality of the surface layer, which is determined by technological methods of the processing; k – the coefficient showing how much the value of the dimensionless complex changes from the initial state Δ_{out} to the operational state of the working relief Δ_{exp}:

$$k = \Delta_{out} - \Delta_{exp}. \tag{2}$$

The value of Δ_{exp} is determined by the wear conditions (speed, pressure, lubrication, and friction pair material, their physical and mechanical properties). Therefore, it can be argued that this coefficient relates the magnitude of the change of the dimensionless complex Δ with the conditions of the friction and wear process.

Studies of the microhardness of the surface in the process of burnishing after various methods of finishing showed that the pattern of its change has a similar character as in round grinding, with the formation of optimal values of microhardness. Thus, the proposed method of analyzing the wear resistance of the conjugate surfaces of parts to ensure the maximum duration of the period of stable operation by assigning technological modes of machining is confirmed by experimental data. It can be used in the design of technological processes for the manufacture of parts.

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Please use the proof correction marks shown below for all alterations and corrections. If you wish to return your proof by fax you should ensure that all amendments are written clearly in dark ink and are made well within the page margins.

Instruction to printer	*Textual mark*	*Marginal mark*
Leave unchanged	• • • under matter to remain	✓
Insert in text the matter indicated in the margin	⋏	New matter followed by ⋏ or ⋏ⓧ2
Delete	/ through single character, rule or underline or ⊢—⊣ through all characters to be deleted	∂/ or ∂/ⓧ2
Substitute character or substitute part of one or more word(s)	/ through letter or ⊢—⊣ through characters	new character / or new characters /
Change to italics	— under matter to be changed	⌙
Change to capitals	≡ under matter to be changed	≡
Change to small capitals	= under matter to be changed	=
Change to bold type	∼ under matter to be changed	∼
Change to bold italic	≂ under matter to be changed	≂
Change to lower case	Encircle matter to be changed	≢
Change italic to upright type	(As above)	⊹
Change bold to non-bold type	(As above)	∔
Insert 'superior' character	/ through character or ⋏ where required	Y or ⅄ under character e.g. Y² or ⅄²
Insert 'inferior' character	(As above)	⋏ over character e.g. ⋏₂
Insert full stop	(As above)	⊙
Insert comma	(As above)	,
Insert single quotation marks	(As above)	Y‘ or ⅄‘ and/or Y’ or ⅄’
Insert double quotation marks	(As above)	Y“ or ⅄“ and/or Y” or ⅄”
Insert hyphen	(As above)	⊢-⊣
Start new paragraph	_⌐	_⌐
No new paragraph	↩	↩
Transpose	⊔⊓	⊔⊓
Close up	linking ⁀‿ characters	⁀‿
Insert or substitute space between characters or words	/ through character or ⋏ where required	Y
Reduce space between characters or words	| between characters or words affected	⊤