



An Increase in Wear Resistance Frictional Contact of Functional Surfaces for Plunger Pairs

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Abstract. A comprehensive approach to the technological wear resistance of parts is based, on the one hand, on the assessment of quality indicators of parts that characterize their geometric shape, surface layer quality, and volumetric properties, depending on technological factors, and, on the other hand, on performance characteristics: contact stiffness, corrosion resistance of parts depending on their quality indicators. In order to do this, considering the mutual influence of quality indicators, changes in one indicator depending on another and changes in the second indicator depending on the first, which are manifested in the same technological transition, such effects significantly affect the values of quality indicators, especially in the manufacture of precision details. A method for estimating the contact interaction of friction plunger pairs is proposed, which considers microgeometric parameters and physical and mechanical properties of the surface layer of conjugate parts based on the theory of the elliptical shape of the microprojections of the surface layer. Modeling the process of contact interaction of coaxial sliding contact of two surfaces, in the form of contact of a cylindrical plunger and a sleeve with equivalent values of parameters of roughness, undulation, and macrodeviations is given. As a result of the comparison of calculated and actual values of wear resistance parameters, the suitability of this approach for modeling of processes of contact interaction of friction surfaces is confirmed. The results confirming the adequacy of the offered model are presented.

Keywords: Wear resistance · Roughness · Waviness · Modeling · Tangential surfaces · Plunger pair · Contour area

1 Introduction

The element of fuel supply regulation in gas turbine engines is a plunger pair, consisting of two parts: a spool and a bushing (Fig. 1). The operation period of the whole unit depends on the quality of operation of this unit because due to the increase in fuel supply to the system increases fuel consumption, temperature load increases, which causes accelerated wear of the unit and repair work. The service life of the plunger assembly depends on the wear resistance of the spool and the sleeve.

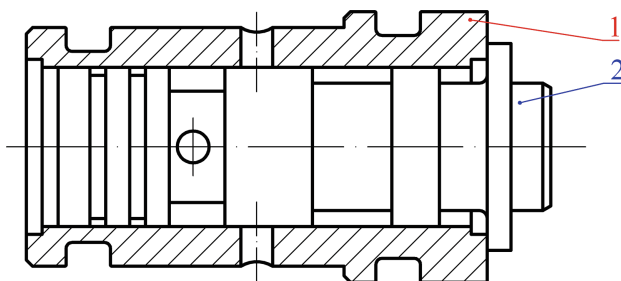


Fig. 1. Fuel supply plunger: 1 – bushing; 2 – valve.

Details of this pair in 80–85% of failure are due to their intensive wear. Due to the lack of durability of parts, there is an economically unjustified, high level of scheduled works [1–3]. The characteristics of cylindrical plunger pairs depend on the type of contact interaction of the conjugate surfaces of the parts, vibrational operating conditions [4], and the quality of their surface layer [5, 6]. A significant number of models are known for analyzing and evaluating frictional interaction, but the vast majority of existing models are adequate only for planar surfaces. Thus, research and development of models for cylindrical conjugate surfaces of parts is an urgent task.

2 Literature Review

During the wear of the tangent elements of the friction units, their shape is subject to specific changes [7]. These changes lead to so-called forms of “natural” wear [8, 9]. Approaching the configuration of the worn part to the one that occurs or to which the part of the friction unit tends allows to reduce the running-in period and significantly increase the service life in the mode of the established wear process [10]. The general approach to choosing rational forms of wearing parts with curved surfaces is considered to ensure minimum friction power and wear speed in the direction of convergence of the mating parts (for plunger pairs to which axial force and reciprocating motion are applied) [11, 12]. Due to the presence of undulation and roughness on the tangential surfaces, the contact of conjugate bodies is discrete; so, the contact zones should be considered according to the law of distribution of contact pressure [13]. Therefore, the model of surface layer roughness can be represented by a set of elliptical protrusions, and they must be described by parameters that characterize their geometric shape [14, 15]. Therefore, it is advisable to use a methodological approach to determine the statistical tests of the characteristics of the contact interaction of tangential surfaces: geometric, nominal, contour, actual contact areas; convergence of conjugate surfaces; pressure distribution along their surfaces; wear rate of tangential surfaces.

3 Research Methodology

The object of the study was a pair operating in the conditions of ultimate friction: R_d - 0.8 MPa; v_d - 0.9 m/s; oil - 5W20. The material of conjugated parts - steel X102CrMo17, hardness HRC = 58...60. Wear tests were performed on the machine VNIPP - 542 according to the scheme of friction of the plunger pair. Initially, two series of specimens with different hardness and five samples in each series were examined. All samples were finally processed by round grinding (v_{cr} - 30 m/s; v_d - 25 m/min; s_{pr} = 0.03 mm/rev; t = 0.02 mm).

For simplifying and visualize the result, it is necessary to choose a model of a single protrusion from a number of elementary geometric figures. At the beginning of the study, models of elementary surfaces with irregularities in spherical segments, rods, pyramids, ellipsoids were selected. The spherical, cylindrical, and ellipsoidal models most completely satisfy all conditions from the offered variants of forms of inequalities. The spherical model contains the error of changing the radius of curvature in the longitudinal and transverse directions, which are equivalent to the radius of rounding [8, 16]. The cylindrical model assumes the average size of the actual contact zone when the load changes, which contradicts the obtained experimental data [10, 17].

The ellipsoidal model is the most adequate for those surfaces, the technology of shaping connected with cutting and grinding. The analysis of these models allows claiming that when calculating the contact area. The results of the rod model differ from the results of the ellipsoidal model by 25–30%. The calculations of the spherical model from the ellipsoidal one by 10–15%. So the ellipsoidal model is chosen.

4 Results

The simulation of the contact interaction process is performed on the example of coaxiality sliding contact of two surfaces of rotation, in the form of contact of a cylindrical plunger and a sleeve with equivalent values of roughness parameters, undulation, and macro deviations. This takes into account the elastic deformations of tangent bodies, as well as elastic-plastic deformations of micro-irregularities.

In the process of modeling the geometric contact, an elementary section of the surface located along the plane in cross-section forming through its center is considered. Assuming that the contact interaction occurs similarly on the whole conjugate surface, therefore, a scale factor was introduced:

$$K_O = 400A/(\pi R p Smw tmw) \quad (1)$$

where A is the geometric area of the contact; R the radius of the tangent spheres; Smw , tmw - undulation parameters; p is the ratio of the lengths of the sides of elliptical paraboloids.

The nominal contact area is determined from the assumption that one of the spheres has the total value of macro deviations H_{max} and acquires the shape of an ellipsoid due to their presence, the major half-axis of which is the contact angle equal to 0 or 90° in the polar coordinate system (Fig. 1). If it is assumed that the total value of macro deviations was small in comparison with the value of the radius R , then (from Fig. 2) it is obtained:

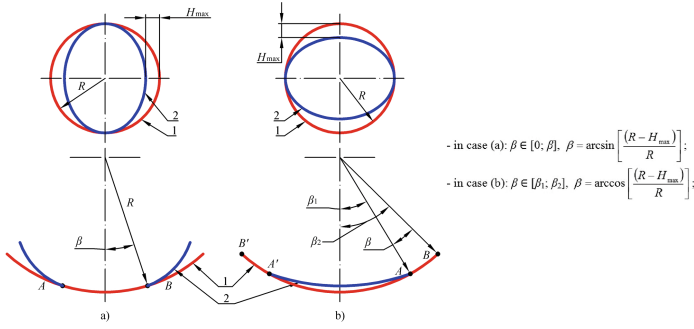


Fig. 2. Contact of tangential surfaces in the presence of macro deviations: 1, 2 - tangent cylindrical surfaces of plunger pair; AB, AB' - areas of the contact surface; R the radius of the sphere; β, β_1, β_2 - angles that define the areas of the contact surface.

In the areas of the nominal contact area, there is roughness and undulation, the model of which is a set of deformed under load elliptical paraboloids of the 2nd order, the vertices of which have a particular distribution law (Fig. 3).

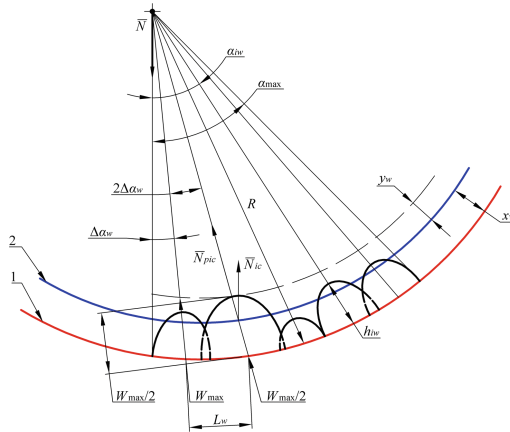


Fig. 3. The scheme of contact of cylindrical surfaces at $\beta \in [0; \beta]$ 1, 2 - tangential surfaces of friction; y_w - the convergence of contact surfaces; x_w the cross-sectional level of the surface model; $\bar{N}$ - external load; α_{iw} - zone of nominal contact area; $\alpha_{\max}$ - contact area; R - radius of the sphere; y_w - the magnitude of the approximation of the tangent surfaces; x_w - the cross-sectional level of the surface model; $\bar{N}_{pic}$ - the reaction of elementary inequality; $\bar{N}_{ic}$ - the reaction of the elementary plane; h_{iw} - the height of the protrusion of the model of the wavy surface; L_w - the average step on the vertices of the local protrusions of the undulation.

For this model, the slice obtained from the cross-section of the functional profile with a plane perpendicular to the middle plane are paraboles of the 2nd order, and the plane parallel to the middle plane are ellipses (Fig. 4). The expression characterizes the cross-sectional area of the i -th paraboloid at the level of x_w :

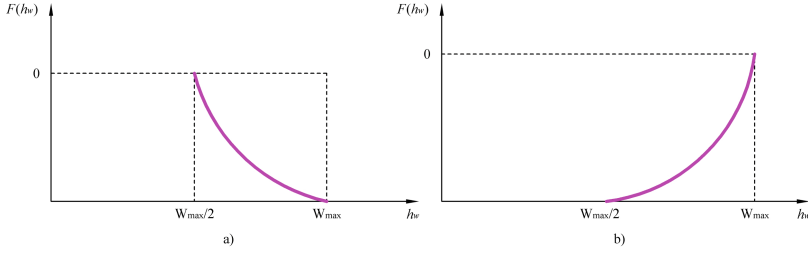


Fig. 5. The density of distribution of heights of ledges of the model (a), the function of distribution of ledges of a model (b).

The value of the height of the protrusions will be determined by solving the equation $F(\xi) = \eta$, where η is a random variable evenly distributed on the segment $[0; 1]$, which is the region of change of the function $F(h_w)$. The random variable ξ has a distribution density similar to $f(h_w)$.

Then:

$$\eta = 1 - \exp(-\lambda[\xi - W_{\max}/2]). \quad (7)$$

From Eq. (7) we obtain:

$$\xi = W_{\max}(0,5 - \ln(1 - \eta)/\lambda). \quad (8)$$

$$h_{iw} = \begin{cases} W_{\max}/2; & \eta = 0; \\ W_{\max}(0,5 - \ln(1 - \eta)/\lambda); & 0 < 1 - \exp(-\lambda W_{\max}/2) < \eta < 1; \\ W_{\max}; & 1 - \exp(-\lambda W_{\max}/2) \leq \eta \leq 1. \end{cases} \quad (9)$$

The distribution parameter λ affects the form of the curve $f(h_w)$ and is determined based on the equality of the relative reference areas of the profile of the actual surface $tp(x_w)$ and model $\tilde{P}_w(x_w)$ at the level of intersection x_w , during the solution of the equation:

$$Z_{\min} = \int_{W_{\max}/2}^{W_{\max}} [\tilde{P}_w(x_w) - tp(x_w)]^2 dx_w. \quad (10)$$

After integration (10) it is obtained the value of λ , which is determined from the equation:

$$0,024\lambda^3 + \frac{0,6b_w(2^{v_w+2} - 1)}{(v_w + 2)2^{v_w+2}} + \frac{b_w(1 - 2^{v_w+2})}{(v_w + 2)2^{v_w+2}} + \frac{1,38b_w(2^{v_w+2} - 1)}{(v_w + 2)2^{v_w+2}} = 0. \quad (11)$$

When the surface configuration is known, the contour area of the contact can be found. The position of the vertices of the protrusions of the model will be determined by the step between the vertices of paraboloids equal to the average step along the vertices of the local protrusions of the undulation L_w (Fig. 3).

$$\Delta a_w = \arcsin[L_w/2R] \quad (12)$$

Assuming that the contour contact area is modeled on the nominal areas bounded by the angle β (Fig. 2), the position of the i -th vertex of the paraboloid will be determined: in the case of (a)

$$\begin{cases} \alpha_{iw} \in [0; \beta], \\ \alpha_{iw} = \Delta\alpha_w, \\ \alpha_{iw} = \alpha_{(i-1)w} + 2\Delta\alpha_w; \end{cases} \quad (13)$$

in the case of (b)

$$\begin{cases} \alpha_{iw} \in [\beta_1; \beta_2], \\ \alpha_{iw} = \beta_1 + \Delta\alpha_w, \\ \alpha_{iw} = \alpha_{(i-1)w} + 2\Delta\alpha_w; \end{cases} \quad (14)$$

The cross-sectional area of the i -th paraboloid for areas of the contour area of contact, limited (13) and (14), taking into account the elastic deformation of the protrusions:

$$P_{ic} = p\pi p_w^2 \left(\frac{h_{iw} - x_w - y_{el.w}}{h_{iw}} \right), \quad (15)$$

where the magnitude of the elastic deformations is equal to:

$$y_{el.w} = (1 - \mu)ck\sigma_T P_{iw} / (\pi E). \quad (16)$$

The reaction of each speech:

$$N_{ic} = ck\sigma_T P_{iw} \left(1 + f^2 \right)^{0.5} \cos \alpha_{iw}, \quad (17)$$

where f is the coefficient of friction.

The surface roughness is modeled in the areas of the contour contact area, similar to the method of modeling the undulation. To do this, in the expressions (1)–(12) it is necessary to replace the values of K_o , Sm_w , tm_w , P_{iw} , p_w , h_{iw} , x_w , $W_{\max}$, h_w , λ , $\tilde{P}_w$, b_w , v_w , $\Delta\alpha_w$, L_w by the values of K_{or} , Sm , tm , P_{irj} , p_r , h_{ijr} , x_r , $R_{\max}$, h_r , λ_r , $\tilde{P}_r$, b , v , $\Delta\alpha_r$, S , respectively.

The actual contact area, the rough surface, will be determined as follows: the position of the vertices of the protrusions of the model will be determined by the step between the vertices of the paraboloids, equal to the average step on the vertices of the local protrusions of the roughness:

$$\Delta\alpha_r = \arcsin [S/2R]. \quad (18)$$

Considering that the actual contact area is modeled at the contour sections, at the intersections of paraboloids that came into contact when modeling a wavy surface (for which $h_{iw} > x_w + y_{el.w}$), the position of the ij -th vertex of the paraboloid when modeling a rough surface (Fig. 6):

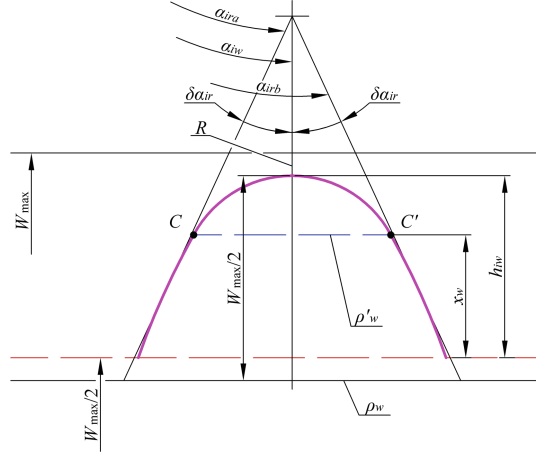


Fig. 6. Surface modeling area on the protrusions of the undulation: CC' - the area of the actual contact area.

$$\begin{cases} \alpha_{irj} \in [\alpha_{ira}; \alpha_{irb}], \\ \alpha_{irj} = \alpha_{ira} + \Delta\alpha_r, \\ \alpha_{ira} = \alpha_{ir(j-1)} + 2\Delta\alpha_r, \end{cases} \quad (19)$$

where $\alpha_{ira} = \alpha_{iw} - \delta\alpha_{ir}$; $\alpha_{irb} = \alpha_{iw} + \delta\alpha_{ir}$; $\delta\alpha_{ir} = \arctg \left[\frac{(p_w(h_{iw} - x_w)^{0.5})}{\{(R - x_w)(W_{\max}/2)\}^{0.5}} \right]$.

The cross-sectional area of the ij -th paraboloid for areas of the actual contact area, limited (19), taking into account the elastic deformations of the protrusions, is equal to:

$$P_{ijr} = \pi p_w^2 (h_{ijr} - x_r - y_{el.r}) / h_{ijr}, \quad (20)$$

where the magnitude of the elastic deformations is equal to:

$$y_{el.r} = (1 - \mu^2) ck \sigma_T P_{ijr} / (\pi E). \quad (21)$$

The reaction of each protrusion of the surface roughness is equal to:

$$N_{ijr} = ck \sigma_T P_{ijr} (1 + f^2)^{0.5} \cos \alpha_{irj}. \quad (22)$$

During the wear of the tangent elements of the friction units, their shape changes. They lead to so-called forms of “natural” wear (Fig. 6). Approaching the configuration of the worn part to the one that occurs or to which the part of the friction unit tends reduces the running-in period and significantly increases the service life in the mode of the established wear process.

For ensuring parameter identification [18] for contact interaction between friction surfaces, the statistical approach [19] can be applied. However, the following algorithm for the developed models of the contact interaction process consisting of seven points is proposed:

1. The input of source data, geometric parameters of conjugate parts; quality parameters of their surface layers; required friction steam performance;
2. Determination of geometric contact using expression (1);
3. Finding the nominal contact area for the two contact options: (a) $\beta \in [0; \beta]$; (b) $\beta \in [\beta_1; \beta_2]$;
4. Determination of the contour area of contact in the nominal areas.

The position of the vertices for paraboloids is calculated by (12)–(14). The height distribution of the protrusions is determined from (9) and (11).

Due to the level of the cross-section $x_w \in [W_{\max}/2; W_{\max}]$ (Fig. 3), the value of the convergence y_w . It estimates the performance of the inequality:

$$|(K_o \Sigma N_{ic} - N)/N| \leq \varepsilon, \quad (23)$$

where N is the external load.

In this case, the micro-inequalities that came into contact ($h_{iw} > x_w + y_{el,w}$) are considered. Execution of Eq. (23) indicates the found value of convergence, at which the formed contour contact area can withstand external loads.

5. Determine the actual contact area in the contour areas. For the paraboloids of a wavy surface which have come into contact ($h_{iw} > x_w + y_{el,w}$ value x_w is defined at the performance of inequality (23)), the position of vertices of paraboloids for a rough surface on (18), (19) and distribution of heights of ledges according to (9), (11) from taking into account the substitution in the data of the expressions of the corresponding roughness parameters. The value of convergence y_r , determined by the level of the section, is given $x_r \in [R_{\max}/2; R_{\max}]$, and the fulfillment of the inequality is estimated:

$$|(K_{or} \Sigma N_{ijr} - N)/N| \leq \varepsilon, \quad (24)$$

In this case, the zones that came into contact are considered, for which $h_{ijr} > x_r + y_{el,r}$. Execution of inequality (24) indicates that the found value of the convergence at which the actual contact area was formed can withstand external loads.

6. Distribution of contour pressures along the generating surface. Under the action of the load, there is not only plastic deformation of the vertices of individual protrusions but also elastic immersion of the zone of plastic deformations in the base metal. In the process of plastic deformation, the pressure is constant and equal to $kH\mu_0$. For elastic deformation of the protrusions forming the contact area in the form of an ellipse, the contour pressure along the generating surface is determined by:

$$q_c(\alpha) = 0,3K_e(\Sigma_{KW}y_r)^{0,5}I^{-1}\cos\alpha_i, \quad (25)$$

where the elastic constant $I = \frac{(1-\mu_1^2)}{(\pi E_1)} + \frac{(1-\mu_2^2)}{(\pi E_2)}$; the amount of the m'ain curvature $\Sigma_{KW} = \frac{1}{\rho_{w\,tran.}} + \frac{1}{\rho_{w\,long.}}$; rounding radius $\rho_{w\,tran.}$, $\rho_{w\,long.}$; K_c – convergence factor:

$$y_r = R_{\max}/2 - x_r - y_{el. r}, \quad (26)$$

7. Calculation of the wear rate of conjugate surfaces according to the wear model:

5 Conclusions

A comparison of calculated and actual wear resistance parameters confirmed the reliability of this approach for modeling the processes of contact interaction of conjugate cylindrical friction surfaces.

Knowing the regulated values of the wear resistance of the conjugate pair and using the model of contact interaction, it is possible to find the values of the parameters k and C_x , which are necessary to ensure the required wear resistance. It is not necessary to perform field tests. Depending on the regulated values of the surface layer hardening coefficients k and the parameter C_x , the choice of technological methods and modes of machining is made. Each of these technological methods of processing has its characteristics and areas of application, characterized by certain factors that determine the process of forming the quality parameters of the treated surfaces of parts. Each of the factors is characterized by its quantitative and qualitative characteristics: regulated height and step parameters of irregularities, the degree and depth of hardening, magnitude, sign, and depth of residual stresses. The proposed approach allows by performing statistical tests on simulation models to perform a scientifically rational choice of technological methods and processing modes.

It is planned to check the simulation results by performing technological operations on prototypes, taking into account the recommendations for selecting technological operations and modes.

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