ARCHIVE OF MECHANICAL ENGINEERING

Volume 67 2020 Number 2

DOI: 10.24425/ame.2020.131688

Key words: functional-oriented technology, operational properties, wear resistance, friction, tribo-contact, profile roughness parameters

Vadym Stupnytskyy[1], Ihor Hrytsay[1]

Comprehensive analysis of the product's operational properties formation considering machining technology

Product Lifecycle Management (PLM) system requires consideration and ensuring efficient operating conditions for the most loaded parts in the product, not only at the product's design stage, but also at the production stage. Operational properties of the product can be significantly improved if we take into consideration the formation of the functional surfaces wear resistance parameters already at the planning stage of the technological process structure and parameters of the product's machining. The method of constructing predictive models of the influence of the technological process structure on the formation of a complex of product's operational properties is described in the article. The relative index of operational wear resistance of the machined surface, which is characterized by the use of different variants of the structure and parameters of this surface treatment, depends on the microtopographic state of the surface layer and the presence of cutting-induced residual stress. On the example of the eject pin machining it has been shown how the change in the structure of the manufacturing process from grinding to the turning by tool with the tungsten carbide insert affects the predicted wear resistance of the machined functional surface.

1. Introduction

In most of the existing integrated systems of machine-building production preparation, a conventional algorithm of automated technological planning is used, which involves carrying out a number of successive interconnected stages of structural-parametric synthesis. This algorithm assumes that, on the basis of input data (as a result of CAD and CAE-systems: design of the processed product, material, its dimensional-weight characteristics, accuracy of geometrical dimensions

---

✉ Vadym Stupnytskyy, e-mail: Vadym.V.Stupnytskyi@lpnu.ua

[1] Department of Mechanical Engineering Technologies, Institute of Engineering Mechanics and Transport, Lviv Polytechnic National University, Lviv, Ukraine.

and mutual arrangement of surfaces, etc.) in the database, a relevant structural-technological prototype of the product is selected. For this prototype, typical machining process structure and sequence of the unified technological operations are selected from an existing database. At the next stage, the technological process structure is corrected, machining parameters are assigned, processing tools are designed or selected, and programs for CNC machines (CAM-system) are developed. At the same time, the technologist (production engineer) completely overlooks the problems of functional (operational) nature of the production object, rightly considering that the assignment of initial data and boundary conditions for technological planning is the prerogative of the designer only. Therefore, the purpose of the initial data and the boundary conditions for technological planning (in the classical sense there are the requirements of accuracy and quality of product's surfaces) is the prerogative of the designer (or CAD/CAE system) only [1]. However, the classical algorithm, used for making technological decisions, significantly limits the potential of an integrated pre-production planning system, and does not allow for the integrated implementation of the PLM (Product Lifecycle Management) system. Obviously, the prediction of the functional features of the product and the associated assignment of the accuracy and quality norms of operational surfaces is made by the designer a priori. However, even experienced designers are not able to fully evaluate the influence of such important factors as microtopography of surfaces, residual stress and strain of the treated surface layer on such operational indicators as fatigue resistance, wear strength, oil-retaining, corrosion resistance, etc.

Increased durability of movable joints surfaces should be ensured already at the technological process-layout preparation stage, not only at the stage of designing. Taking into account the fact that wear-resistance parameter of the functional surface is the most important factor of efficient functioning of the product when planning the optimal methods for its machining, one can increase the operational properties of the product according to the PLM conception. However, the achievement of this goal is complicated due the following reasons: the complexity and adequate formalization of the mathematical models connecting the indicators of wear resistance with the characteristics of surface quality and technological cutting parameters, the diversity of approaches to describe the physics of wear processes, the incoherence and ambiguity of information on indicators of wear resistance, multi-choice solutions, the use of different criteria when describing the conditions of wear, characteristics of surface quality, machining methods, etc. Therefore, the primary task for design and technological provision methods to improve wear-resistant properties should be systematization of data (information) on the forecast mathematical model of the wear process and using them as initial data for the functionally-oriented technological process planning.

Based on the above, the main task of the present study is the determination of the formalized relationship between the machining process parameters and the functional properties of the product. This will allow us to determine such a criterion of optimality of the structure and parameters of technological process that will give a possibility to provide the most effective conditions of wear resistance of the most loaded surfaces of the product under the specified future operating conditions. It is obvious that such a task is complex and multilevel. It is necessary to identify exactly what are the technologically dependent factors of the surface layer of the treated surface (microgeometric and physical-mechanical) and how much they can affect the wear resistance of the manufactured article. In addition, it is necessary to forecast the most characteristic conditions of contact formation of movable surfaces (the state of elastic or plastic contact) under the expected operating conditions. At the same time, the criterion of optimality of the functionally-oriented technological process should be relevant and take into account only essential components in the formal representation of the wear resistance parameter (which depend on the structure and parameters of the technological process). Similar studies should also be carried out for other parameters of effective functioning of the product (fatigue strength, corrosion resistance, provision of oil-retaining layer, etc.). However, this is a topic for other studies.

2. Literature review

In the recent years, a qualitatively new direction of the mechanical engineering science has been formed, which consists in the development of scientific foundations for planning technological processes of machining parts with the most effective operational properties [1–3]. Creation and implementation of scientific and applied principles of the functional-oriented technologies planning for the integrated increase of operational quality of machine-building products is the topical engineering task. The target function in making decisions about the optimal structure and parameters of a function-oriented technological process is an integral index that systemically characterizes such part's properties as wear resistance, fatigue strength, corrosion resistance etc. [2]. These parameters are estimated with the viewpoint of operational surface layer state after machining, thermodynamic state of the treated surface, and machining-induced residual stresses and strains.

The topic and direction of research on the formation of product's operational properties on the technological planning stage are considered in many literary sources [4–6]. It is possible to determine the conditions and modes of forming, which ensure the achievement of the specified parameters of durability of machine parts in the probable operating conditions knowing the influence of technological factors on the quality of the machined surface. A significant influence have the formed roughness parameters of the contacting surfaces in the conditions of dry or boundary friction between them. Dry friction occurs because, in small gaps with a slight roughness, the lubricant is squeezed out from the contact area. As a result, in the areas of direct contact of surfaces, strong metal bonds are formed, that is, their grasping takes place. This, in turn, causes a more intense wear of the part's operational surfaces. Phenomenological friction theory considers this effect as a process of energy dissipation, proceeding with relative tangential displacement of the contact surfaces, which is carried out in the zones of real contact [7]. These zones are created both because of the external loads influence and as a result of the internal interaction of the loaded surfaces in contact [8].

The scientific work [2] presents studies on the nature of the surface that results from manufacturing processes, as this nature has long been recognized as having a significant impact on the product performance, longevity and reliability. Surface alterations may include mechanical, metallurgical, chemical and other changes. These changes, although confined to a small surface layer, may limit the component's quality or may, in some cases, render the surface unacceptable. A basic understanding of the changes in the condition of the surface is mostly required if improvement in product quality is to be attained. Surface integrity reveals the influence of surface properties and condition upon which materials are likely to perform. It has been known that the method of surface finishing and the complex combination of surface roughness, residual stress, cold work, and even phase transformations strongly influence the service behavior of manufactured parts, such as wear resistance and fatigue deformation. Various manufacturing processes applied in industry produce the desired shapes in the components within the prescribed dimensional tolerances and surface quality requirements. Surface topography and texture is the foremost characteristic among the surface integrity magnitudes and properties imparted by the tools used in the processes, machining mostly, and especially their finishing versions. It should also be considered from two standpoints, i.e., process control and tribological function, in the context that to achieve the proper functionally-oriented surface, the appropriate manufacturing method must be applied along with the inverse problem of controlling the forms of texture for various processes planning.

Obviously, the manufactured surface is not perfectly flat (round). As a result, the real contact area of two manufacturing surfaces in contact is normally much smaller that the apparent contact area, as these surfaces are contacted by their asperities. This results in the constancy of the friction coefficient of a pair of manufactured surfaces over a wide range of normal pressures [2, 8]. Due to the elastic deformation of the asperities, the actual contact area (and thus the friction force) increases with the normal pressure keeping the same friction coefficient as the ratio of the frictional and normal forces. Chemisorbed and adsorbed layers on a manufactured surface serve as a boundary-layer lubricant that significantly reduces the bonding forces in the contact [2].

It has been proved [9–11] that, when the rough surfaces under load are drawn together, first of all only highest peaks touch with one another which undergo to significant local pressure (Fig. 1a). This leads to a significant compression of the asperities and to the introduction of contact interaction between the next surface peaks. This phenomenon occurs until the total contact area provides the bearing capacity of the surface in accordance with its dimensions, applied externally load, contact conditions, physical and material's mechanical properties of the parts in contact (Fig. 1b). As the research works [9, 10] show, the actual contact formed in such a way is almost two orders of magnitude smaller than the nominal one. Increased roughness may, under certain circumstances, result in weaker frictional interactions, while smoother surfaces may in fact exhibit high levels of friction owing to high levels of real contact.

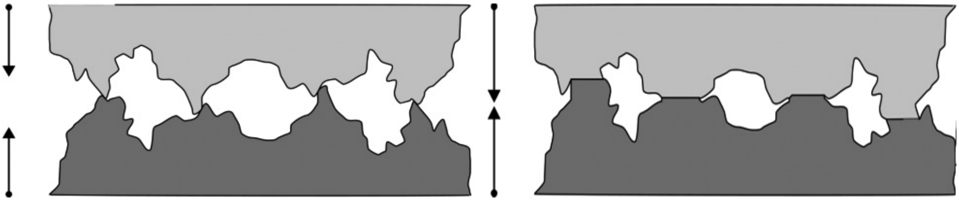

(a) (b)

Fig. 1. Trace of asperities without (a) and after applying (b) a load

In view of the above, an important objective of such studies is to evaluate the mutual influence of the main process parameters on the wear resistance of functional surfaces in sliding joints. Typically, the effect of the cutting parameters during machining of the part on the wear resistance parameters of the articles is evaluated based on one- or multi-factor experiments [1]. This way is too expensive and long. Therefore, the main proposal described in this article is the method of formalizing predictive models of influence of the mechanical technology structure and parameters on formation of operational properties of the product.

3. Research methodology

To solve the foregoing problem, it is first necessary to determine which important parameters of wear resistance depend on the structure and parameters of the product's machining technological process. Therefore, firstly we consider the generalized model of wear and select the technology-dependent parameters.

The idea of rough equivalent surface is most effective for simplifying the calculation of the actual area between the surfaces in contact. Such a contact is approximated as a contact of an equivalent surface and an ideally-smooth surface [10, 11]. The equivalent surface has a roughness, which determined by adding both surfaces in contact. This method is based on the step approximation of the bearing area η according to the Abbott-Firestone curve using the approximating coefficients b and ν_p, and described such that [12, 13]:

$$\eta = b\,\varepsilon^{\nu_p}. \tag{1}$$

The Abbott-Firestone curve or bearing area curve (BAC) describes the surface texture of an object. The curve could be found from a profile by drawing lines parallel to the datum and measuring the fraction of the line which lies within the profile [14].

Parameters b and ν_p are related to the roughness parameters by correlations:

$$b = tm\left(\frac{R\mathrm{max}}{Rp}\right)^{\nu_p}, \tag{2}$$

$$\nu_p = 2\,tm\,\frac{Rp}{Ra} - 1, \tag{3}$$

where tm is the bearing length ratio at the mean line; Rmax is the maximum peak-to-valley profile height (the greatest peak-to-valley distance within any one sampling length); Rp is the highest peak (the maximum distance between the mean line and the highest point within the sample. It is the maximum data point height above the mean line through the entire data set); Ra is the arithmetical mean deviation (the arithmetic average of the absolute values of the roughness profile).

To produce a bearing area curve from the real surface profile, a parallel line (bearing line) is drawn at some distance from a reference (or mean) line. The length of each material intercept along the line is measured and these lengths are summed together. The proportion of this sum to the total length, the bearing length ratio (tp), is calculated. This procedure is repeated over a number of bearing lines starting at the highest peak to the lowest valley and the fractional land length (bearing length ratio) is plotted as a function of the height of each slice from the highest peak (cutting depth) [15].

For the parameters b and ν_p of equivalent surface, the following relations are formulated as [16]:

$$b = k\,b_1\,b_2\left(R\mathrm{max}_1 + R\mathrm{max}_2\right)\frac{\nu_{p1}+\nu_{p2}}{R\mathrm{max}_1^{\nu_{p1}}\;R\mathrm{max}_2^{\nu_{p2}}}, \tag{4}$$

$$\nu_p = \nu_{p1} + \nu_{p2}, \tag{5}$$

where $k = \dfrac{\Gamma\left(\nu_{p1}+1\right)\Gamma\left(\nu_{p2}+1\right)}{\Gamma\left(\nu_{p1}+\nu_{p2}+1\right)}$. $\Gamma(\cdot)$ is the gamma-function, which is defined for all complex numbers except the non-positive integers [17].

Thus, we can approximate the complex profiles of the two contact surfaces to the single simple profile of the rough surface, which is described by the virtual indicators b and ν_p. This virtual surface will touch an absolutely smooth surface (without roughness). It is obvious that every peak deforms first of all elastically, and then plastically. However, we can take into consideration that the peak will be deformed only elastically, if the following condition is met [18]:

$$\frac{R\mathrm{max}}{r^2} < K_m\frac{\sigma_T\left(1-\mu^2\right)}{E}, \tag{6}$$

where r is the contact spots radius; σ_T is the yield stress of the material; K_m is a coefficient that depends on conditions of strain [18]; μ is the Poisson's ratio; E is the Young's modulus.

Another criterion for transition from an elastic contact to a plastic one may be the index of plasticity calculated from the Greenwood and Williamson Contact Model [19, 20]. In this case, the plastic fluidity of the asperities begins when the maximum Hertz pressure $q_{\max}$ reaches a value of $0.6H$ (H – hardness of the softer of the two contact materials). Taking into consideration the approximation model of the conical form of peak-to-valley profile roughness, we find that the distance between mean lines of contact profiles is related to pressure as:

$$y = \frac{\pi^2}{4} \frac{q_{\max}^2 \mu}{E^2} . \tag{7}$$

Substituting $q_{\max} = 0.6H$, we obtain a critical distance:

$$[y] = 0.89\mu \left(\frac{H}{E}\right)^2 . \tag{8}$$

To calculate contact deformations, it is necessary to classify geometric form of the surfaces in accordance with the form of simulated roughness obtained as a vector sum of geometric-kinematic, vibrational and deformation components. For them, typical models according to cutting method of machined surface have been developed [2]. Modeling the interaction between a conical surface and a plastic half-space, we solve the task based on the A. Ishlinsky algorithm [21]. K. Chill's method is used to model the interaction between the wedge and the plane surface [22].

Thus, under the condition of elastic contact of the spherical projections, one can calculate the specific contact pressure according to the Hertz formula [18, 21]:

$$q_r = 0.43\sqrt{\frac{y}{I^2\, J}}\,, \tag{9}$$

where:

$$I = \frac{1-\mu_1^2}{E_1} + \frac{1-\mu_2^2}{E_2}\,; \qquad J = \frac{R_1\, R_2}{R_1 + R_2}\,, \tag{10}$$

where R_1, R_2 are radiuses of assembly surfaces in contact; y is the distance between mean lines of profiles.

The Mayer's formula is used to determine the contact pressure in the case of only plastic strain of asperities [23]:

$$N_i = g d^{\vartheta}, \tag{11}$$

where N_i is the load on the indenter; d is the diameter of the indentation; g, ϑ are coefficients characterizing the plastic property of the material.

Therefore, we can use the formula for the cylindrical surfaces [21]:

$$N_i = (8Rp)^{\vartheta/2}\, g \varepsilon^{\vartheta/2}, \tag{12}$$

where N_i is the load on the indenter; d is the diameter of the indentation; g, ϑ are coefficients characterizing the plastic property of the material.

Then, the contact pressure is given by:

$$q_r = \left(\frac{2H_M^{1/m_1} Rp}{\alpha_r} \varepsilon \right)^{m_1}, \tag{13}$$

where $m_1 = \vartheta/2 - 1$; H_M is the Mayer's index (hardness, obtained under the condition that indentation of the sphere extends to the equator – $d = D$).

$$g = \frac{\pi H_M}{4D^{\vartheta-2}}, \tag{14}$$

Thus, the Hertz formula is given by:

$$q_r = B(\varepsilon)^{\omega}, \tag{15}$$

where B and ω are the coefficients that depend on the form of the roughness, physical and mechanical properties of the material, respectively.

The general formula for convergence of the contact surfaces with a classical elastic-plastic contact is determined by the formula [18]:

$$y = \frac{N}{2\pi r C\sigma_T} + \frac{3}{8} I \sqrt{N\pi C\sigma_T}, \tag{16}$$

In this formula, the first part defines the plastic component of the deformation, and the second one – the elastic component.

The limit elastic load acting on a single peak can be described by the formula:

$$N_i = q_r \Delta A_{ri} = B\,(\varepsilon_i)^{\omega}\,\Delta A_{ri}, \tag{17}$$

where $\varepsilon = \dfrac{y_i}{Rpk}$ is the relative approach of mean lines of micro-profiles; ΔA_{ri} is the actual area of contact spot.

Taking into account that the average value of peak-to-valley height differs from the maximum value of $Rpk_{\max}$, the full load can be calculated by summing the loads at separate peaks and taking into account that $dN_i = N_i dn_r$. After integrating with the contacted peaks and taking into account the equivalence conditions (4) and (5) defined as:

$$N = \frac{\Gamma(2+\omega)\Gamma(\nu+1)}{\Gamma(\nu+\omega+1)} \alpha\, tm\, A_c\, B\, \varepsilon^{\omega+\nu}, \tag{18}$$

alternatively, taking into consideration the constant $K_3 = \dfrac{\Gamma(2+\omega)\Gamma(\nu+1)}{\Gamma(\nu+\omega+1)}$, we can make next transformation:

$$N = K_3\, \alpha\, tm\, A_c\, B\, \varepsilon^{\omega+\nu}. \tag{19}$$

Thus, the formula for relative approach of mean lines is defined as:

$$\varepsilon = \left(\frac{q_r}{\alpha\, K_3\, tm\, B}\right)^{1/(\omega+\nu)} . \tag{20}$$

The relative contact area can be described as:

$$\eta = \alpha^{\frac{\omega}{(\nu+\omega)}}\, tm^{\frac{\omega}{(\nu+\omega)}}\, q_r^{\frac{\nu}{(\nu+\omega)}}\, K_3^{\frac{(\nu+\omega)}{\nu}}\, B^{\frac{(\nu+\omega)}{\nu}} , \tag{21}$$

where α is the ratio of peak's elasticity (it is possible to accept conditionally $\alpha = 0.5$ in the case of elastic contact, provided that the Williamson-Greenwood criterion is satisfied, or $\alpha = 1.0$ in the case of plastic contact, provided that the plasticity index is more than $0.6H$.

Thus, the formulas (1)–(3) should be modified for the simulation of the tribo-contact, taking into consideration the need to describe an equivalent surface in accordance with the Dyomkin model [18]:

$$\nu_{ekv} = \nu_1 + \nu_2 ; \tag{22}$$

$$tm_{ekv} = K_p\, tm_1\, tm_2 ; \tag{23}$$

$$Rpk_{ekv} = K_p\, Rpk_1\, Rpk_2 ; \tag{24}$$

$$K_p = \frac{(Rpk_1 + Rpk_2)^{\nu_{ekv}}}{Rpk_1^{\nu_1}\, Rpk_2^{\nu_2}} ; \tag{25}$$

$$b_{ekv} = \frac{(R\text{max}_1 + R\text{max}_2)^{\nu_{ekv}}}{R\text{max}_1^{\nu_1}\;\; R\text{max}_2^{\nu_2}} ; \tag{26}$$

$$Rvk_{ekv} = K_v\, Rvk_1\, Rvk_2 ; \tag{27}$$

$$K_v = \frac{(Rvk_1 + Rvk_2)^{\nu_{ekv}}}{Rvk_1^{\nu_1}\, Rvk_2^{\nu_2}} ; \tag{28}$$

$$Rk_{ekv} = Rk_1 + Rk_2 . \tag{29}$$

The average bearing area depends on the tribo-contact loading and this value varies from 1 to 0.2, with the dominant influence of the peak-to-valley profile roughness rather than their height and spacing parameters. In addition, it is known [18] that the contact interaction is determined only by the size of the gap between the contacting bodies. Therefore, the equivalent modulus of elasticity is defined as:

$$E_{ekv} = \frac{1}{\left(\dfrac{1-\mu_1^2}{E_1}\right) + \left(\dfrac{1-\mu_2^2}{E_2}\right)} , \tag{30}$$

where E_1 and E_2 are the moduli of elasticity (Young's moduli) for the bodies in contact; μ_1 and μ_2 are Poisson ratios for the contacting bodies.

The linear wear rate is defined as:

$$I_h = \frac{y}{L}, \tag{31}$$

where y is the value of the wear layer (absolute approach of mean lines calculated according to formula (16)); L is the distance of mutual movement of the bodies in contact, along which the wear occurs.

The basic formula for calculation of the wear rate is [21]:

$$I_h = i\frac{A_r}{A_a} = i\frac{P_a}{P_r}, \tag{32}$$

where A_a, A_r are the nominal (apparent) and contour tribo-contact area, respectively; P_a, P_r are the nominal and actual pressure, respectively; i is the specific wear calculated as the volume of material is removed from the contour touch area along the length of d:

$$i = \frac{y}{d(\nu + 1)n}, \tag{33}$$

where ν is the parameter for the degree of approximation of the bearing area curve.

The analysis of formulas (32)–(33) proves that the wear rate is determined by the number of cycles that lead to the damage of the part's material and depend on the ratio of the nominal pressure to the actual pressure. The number of cycles depends on the contact stresses and deformations that are associated with friction. The calculation of wear can be carried out based on the simulation of the functional process (such parameters as load, temperature, speed, etc.) via the CAE (Computer Aided Engineering) systems [24, 25].

For the elastic tribo-contact, the number of cycles to full damage is given by:

$$n = \left(\frac{\sigma_0}{k\,f\,P_r}\right)^t, \tag{34}$$

where σ_0 is the initial extrapolated stress value at $n = 1$; f is the coefficient of friction for sliding; k is the ratio which depends on the physical and mechanical properties of the material.

So, for brittle materials (brittleness index $t_x \geqslant 2$) we accept $k = 5$; for conditionally brittle materials ($1 \leqslant t_x < 2$) we accept $k = 4$; for plastic materials ($t_x < 1$) we accept $k = 3$ [21]. However, for materials which allow for the appearance of significant plastic strains but work in an elastic area, and only for the case for the Greenwood and Williamson Contact Model condition (formula (6)):

$$k = 1.5\sqrt{4\left(1 - \mu - \mu^2\right) + \frac{(1 - 2\mu)^2}{f^2}}, \tag{35}$$

where μ is the Poisson's ratio.

Then, for elastic contact, the wear rate is given as [26]:

$$I_h = \frac{c_1 P_a^{1+\gamma t}}{\chi} (\Gamma)^{f-\gamma t-1} \left(\frac{kf}{\sigma_0 c_2}\right)^t \lambda \Delta^{\gamma t \nu}, \tag{36}$$

where the equivalent index γ is given as:

$$\gamma = \frac{1}{2\nu_{ekv} + 1}, \tag{37}$$

in addition, constants c_1 and c_2:

$$c_1 = \frac{3\pi\sqrt{\nu_{ekv}}}{8k\left(\nu_{ekv} + 1\right)}; \qquad c_2 = 0.5\left(\frac{3\pi}{2k}\right)^{2\nu_{ekv}\gamma}. \tag{38}$$

Δ_{ekv} is the dimensionless index characterizing the equivalent roughness:

$$\Delta_{ekv} = \frac{R\text{max}_{ekv}\, b_{ekv}^{\nu_{ekv}}}{r}. \tag{39}$$

λ is the ratio depended on surface's residual stress. This gives:

$$\lambda = \left(\frac{\sigma_{UT} - \sigma_r}{\sigma_{UT}}\right)^{t_y}, \tag{40}$$

where σ_r is the residual stress formed as a result of the cutting or deformation process of a specific surface; σ_{UT} is the Ultimate tensile strength; t_y is the ratio of frictional fatigue under the elastic contact of surfaces.

In simplified form, formula (36) can be written as:

$$I_h = \frac{0.6\left(1-\mu^2\right) P_a \lambda}{\sqrt{\nu_{ekv}}\left(\nu_{ekv}^2 - 1\right) K_2 E n}. \tag{41}$$

Formula (41) can be simplified for surfaces with very low roughness ($Ra = 0.1$ . . . 0.5 µm), whose values of the coefficients are $\nu_{ekv} = 3$, $\mu = 0.3$, $K_2 = 0.12$:

$$I_h = \frac{0.6 P_a \lambda}{E_{ekv}\, n}. \tag{42}$$

Formula (42) may be recommended for approximate wear calculations only. The number of cycles n should be chosen according to the S-N curve (Goodman diagram) [27], taking into consideration that the tensile stress σ_r is approximately equal to $5 f P_r$.

As follows from formula (36), the wear rate when elastic tribo-contact is directly proportional to the nominal pressure P_a, and is inversely proportional to the number of cycles n and the equivalent elastic modulus E_{ekv}.

It can be concluded that, when elastic contact occurs, the wear rate depends on the topography of the profile characteristics of the contact surfaces (b, v, Rmax, tm), the mechanical properties of the materials (σ_0, E, μ), the coefficient of friction f, and on the nominal pressure P_a and the contour pressure P_c.

The volume of the worn-out material V_b can be calculated by the Kragelsky formula [26] (when the Williamson-Greenwood condition (8) is not satisfied, that is, the index of plasticity exceeds the value of $0.6H$):

$$V_b = \frac{\varepsilon\, A_r\, R\mathrm{max}_{ekv}}{\nu_{ekv} + 1}\,. \tag{43}$$

Thus, the wear rate for the plastic contact of the roughness can be described as:

$$I_h = \frac{\alpha\, b_{ekv}\, \varepsilon^{(\nu_{ekv}+1)}\, R\mathrm{max}_{ekv}\, \lambda}{(\nu_{ekv} + 1)\, n\, d}\,. \tag{44}$$

Analyzing formulas (36) and (44), one can be conclude that factors such as external friction conditions, mechanical properties of materials and topography of the contact surfaces have a significant influence on the wear rate value. It is very important that most of these parameters will depended on the structure and parameters of the machining or hardening technological process [28]. However, in the above models, there are no such important characteristics as the speed of sliding and the associated temperature. These parameters can have a great influence on the patterns of wear. Thus, the complex effect of mechanical and thermodynamic factors in simulation CAE-models of parts and assembly units should be taken into consideration.

The wear rate of the product under certain conditions of its operation in the case of the i-th version of the manufacturing process can be written in a simplified form as:

$$I_{hi} = \frac{0.6\left(1-\mu^2\right) P_a\, \lambda_i}{\sqrt{\nu_{ekv\ i}}\left(\nu_{ekv\ i}^2 - 1\right) K_2\, E_{ekv\, i}\, n}\,. \tag{45}$$

Thus, the relative index of operational wear resistance of the machined surface, which is characterized by the use of different variants of the structure and parameters of this surface treatment, is described by the formula:

$$K\left(I_h\right) = \frac{I_{h1}}{I_{h2}} = \frac{\left[\dfrac{0.6\left(1-\mu^2\right) P_a\, \lambda_1}{\sqrt{\nu_1}\left(\nu_1^2 - 1\right) K_2\, E\, n}\right]}{\left[\dfrac{0.6\left(1-\mu^2\right) P_a\, \lambda_2}{\sqrt{\nu_2}\left(\nu_2^2 - 1\right) K_2\, E\, n}\right]} = \frac{\sqrt{\nu_2}\left(\nu_2^2 - 1\right) \lambda_1}{\sqrt{\nu_1}\left(\nu_1^2 - 1\right) \lambda_2}\,. \tag{46}$$

4. Results and discussion

Let's consider an example of the influence of the technological process structure on the value of wear resistance. The object of research is the stepped ejector pin for die casting mold (DIN1530/ISO6751). This important element of the mold structure is subject to intense wear, changeable load and thermal stress, which can cause loss of the functional properties of this mold. Therefore, the most important operational properties of ejector pins are wearing resistance, contact stiffness, fatigue strength and corrosion resistance (corrosion micro-cracking preventing). These operational properties essentially depend on such indicators of surface quality as micro-topography of functional surfaces, microhardness (hardness of the surface layer), residual stresses and strains, their type and depth. Material parts – tool steel DIN X40CrMoV5-1. Shaft Surface Hardness: Min 950 HV 0.3. Core Hardness: 40–45 HRC.

Indicators of the operational surface quality are formed, as a rule, at the final stage of the manufacturing process. The volumetric hardening of a nonrigid ejector pin (the ratio of length to diameter greater than 10), which causes great deformation of the workpiece, is used in the basic technological process. This needs very large (up to 2 mm) allowances in machining of the outer cylindrical surface. Therefore, just the final stage of the pin's machining is considered in this example in detail. Two alternative variants of finishing the most precise cylindrical pin's surfaces can be used:

1-st variant. Finish grinding by the diamond abrasive wheel ACB 125/100 M5-2.

2-nd variant. Superfinish turning by the Sandvik Coromant tool with the tungsten carbide insert CB7025 and Wiper-type edge.

The results of experimental studies of the stepped ejector pin finishing are given in Table 1.

The topography studies of the treated surfaces were carried out using the roughness tester UIT TR300 (resolution – 0.001 µm; accuracy ±5%; filtration type – PCRC, D-P, ISO 13565) and software TIMESurf.

Residual stresses were determined by the ultrasonic acoustic strain measurement [30, 31]. This method consists in the analysis of the change in the velocity of ultrasonic waves resulting from the presence of residual mechanical stresses on the surface of the experimental sample (Fig. 2). Rayleigh surface acoustic waves (R-wave) were used to determine stresses. These waves propagate over the surface of the sample in a layer of 1–2Λ (where Λ is the length of the R-wave). The study used 3 MHz waves, which corresponds to R-wave Λ = 1 mm. The study assumed that the stress lies along the line of the sample, that is, has a one-dimensional character (longitudinal direction only). Thus, the existing residual stress can be calculated according to the formula [29]:

$$\frac{\Delta V_1}{V_1} = \beta_1 \, \sigma_r \,, \tag{47}$$

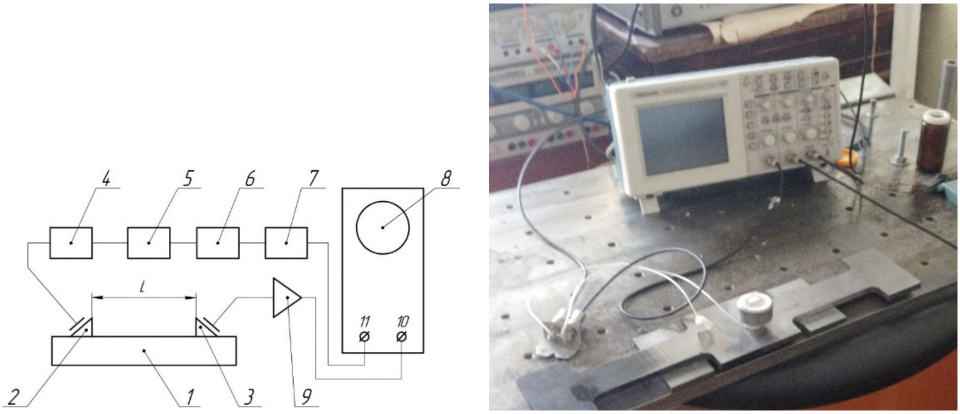
Table 1.

Experimental machining data [29]

Parameters	Superfinish turning	Finish grinding
Ra, µm	1.29	1.22
Rpk, µm	0.28	0.43
Rk, µm	0.84	0.61
Rvk, µm	0.17	0.18
$R\mathrm{max}$, µm	2.0	2.2
r	35	20
b	2.0	1.29
ν	1.7	1.9
$\Delta = \dfrac{R\mathrm{max}}{r\,b^{1/\nu}}$	0.024	0.096
$\pm\sigma_r$, MPa [1]	+143	−130

[1] The marks "+" and "–" are used for the compression and for the tensile cutting-induced residual stresses, respectively.

where V_1 is the velocity of the R-wave which propagates in longitudinal direction of the ejector pin axis; ΔV_1 is the change in the propagation velocity of the R-wave caused by mechanical residual stresses; σ_r is the component of residual mechanical stress tensor; β_1 is the acoustoelastic coefficient [30].



(a) (b)

Fig. 2. Schematic diagram (a) and photograph (b) of experimental device: 1 – experimental sample; 2, 3 – excitation and recording piezoelectric converters; 4 – trigger; 5 – pulse shaper; 6 – time delay unit; 7 – pulse generator; 8 – electron beam oscilloscope

The principle of operation of the experimental device (Fig. 2) is as follows. Pulse generator 7 generates short pulses with amplitude of 35. . . 100 V, which are supplied to the excitation piezoelectric converter 2. The ultrasonic pulse passes along the test sample (machined ejector pin) 1 and, after a period of time τ, reaches the recording piezoelectric converter 3. This device transforms the ultrasonic signal into an electric pulse, which is amplified by the amplifier 9 and supplied to the input 10 of the electron beam oscilloscope 8. At a constant scanning speed, the position of the pulse on the screen depends on the time of transmission of ultrasonic signal along the distance l between the piezoelectric converters 2 and 3, and therefore on the speed of ultrasound propagation in the experimental sample. The expected oscilloscope scanning doesn't start at the moment of generation of the pulse in unit 5, but after a period of time τ_0. This time is shorter than the time the ultrasonic pulse passes the distance between piezoelectric converters (Fig. 2). The time delay of the signal introduced by a special time delay unit 6, which is triggered by a pulse coming from the generator 7 and generates (by the unit 5) a rectangular pulse of duration τ_0. The technique of the study is to measure the velocity of the pulse in the stress-free sample and in the sample with the cutting-induced residual stress [31, 32]. This velocity difference allows for determining residual stress according to formula (47).

To determine the conditions of the tribo-contact, it is necessary to calculate the plasticity index with formula (6). The peaks of roughness will deform completely elastically if the following condition is satisfied:

$$\frac{R\mathrm{max}}{r^2} < K_m \frac{\sigma_F \left(1-\mu^2\right)}{E},$$

where r is the contact spot radius; σ_F is the Flow stress ($\sigma_F = 1390$ MPa for the steel X40CrMoV5-1); K_m is the coefficient that depends on strain conditions (accepted $K_m = 7$); μ is the Poisson's ratio ($\mu = 0.28$); E is the Young's modulus ($E = 1.77 \cdot 10^5$ MPa for the steel X40CrMoV5-1).

For the superfinish turning of the ejector pin by the tool with the tungsten carbide insert CB7025, the condition (6) is implemented:

$$\frac{2.0}{35^2} = 0.0016 < 7\frac{1390\left(1-0.28^2\right)}{1.77 \cdot 10^5} = 0.05.$$

Similarly, for the finish grinding of the ejector pin by the diamond abrasive wheel ACB 125/100 M5-2, tribo-contact can be considered as elastic because the condition (6) is fulfilled too:

$$\frac{2.2}{20^2} = 0.0055 < 7\frac{1390\left(1-0.28^2\right)}{1.77 \cdot 10^5} = 0.05.$$

Thus, under conditions of elastic contact, the wear rate depends on the topography of the profile parameters of the surfaces in contact (b, v, Rvk, Rpk, Rk, *R*max, *tm*), the mechanical properties of the materials (σ_F, σ_{UT}, $\sigma_{0.2}$, E, μ), the coefficient of friction f, fatigue ratio t and pressures – nominal P_a and contour P_c.

The coefficient taking into consideration the effect of cutting-induced residual stresses on the wear rate (when Ultimate tensile strength for steel X40CrMoV5-1 – $\sigma_{UT} = 1530$ MPa; frictional fatigue ratio under elastic contact $t_y = 3$), is calculated with formula (40):

- for superfinish turning:

$$\lambda_1 = \left(\frac{1530 - 143}{1530}\right)^3 = 0.75;$$

- for finish grinding:

$$\lambda_2 = \left(\frac{1530 - (-130)}{1530}\right)^3 = 1.27.$$

The relative index of wear resistance $K\,(I_h)$, which characterizes the wear rate change, depending on the state of functional surfaces, resulting from the implementation of various variants of structures and parameters of the technological process, can be calculated according to formula (46). Comparing the superfinish turning of the ejector pin by the tool with the tungsten carbide insert CB7025 (cutting parameters: $S = 0.05$ mm; $t = 0.12$ mm; $V = 50.2$ m/min) and grinding by the diamond wheel ACB 125/100 M5-2 ($V_k = 31$ m/sec, $t = 0.01$ mm, $S_n = 6$ m/min), we obtain a relative index of wear resistance:

$$K\,(I_h) = \frac{I_{h1}}{I_{h2}} = \frac{\sqrt{1.9}\left(1.9^2 - 1\right)0.75}{\sqrt{1.7}\,(1.7^2 - 1)\,1.27} = 0.86.$$

That is, the wear resistance of the functional surface increases by about 14% because of the change in the structure of the technological process (as a result of replacing finish grinding by superfinish turning). This is the consequence of the change of microtopographic state of the machined surface layer and the presence of cutting-induced residual stress.

5. Conclusions

1. Product Lifecycle Management (PLM) system requires consideration and implementation of the efficient operating conditions (especially wear resistance) for the most loaded parts in the product not only at the product's design stage, but also at the technology planning stage. However, the achievement of this goal is complicated due to the following reasons: the complexity and adequate formalization of the mathematical models connecting the indicators of wear resistance with the characteristics of surface layer state and technological cutting parameters, the

diversity of approaches to describing the physics of wear processes, the incoherence and ambiguity of information on indicators of wear resistance, multi-choice solutions, the use of different criteria when describing the conditions of wear, characteristics of surface quality, machining methods, etc. Therefore, the priority task for planning of the provision methods to increase of product's wear-resistant properties at the production stage should be systematization of data (information) on the forecast mathematical model of the operational wear process and the use of this information as initial data for the functionally-oriented technological process planning. In view of the above, an important objective of such studies is to evaluate the mutual influence of the main machining process parameters on the wear resistance of functional surfaces in sliding joints. Typically, the effect of the cutting parameters during machining of the part on the wear resistance parameters of the articles is evaluated based on one- or multi-factor experiments. This way is too expensive and long. Therefore, the main proposal described in this article is the method of formalizing predictive models of influence of the mechanical technology structure and parameters on formation of the product's effective operational properties.

2. It is proved that, under the conditions of a particular operational situation, it is possible to identify the dominant type of friction that leads to the most intensive wear of a functional surface. In order to detect the priority type of wear in conditions of potential operation of the product, a special condition that follows from the analysis of the destruction kinetics for the surfaces in contact must be taken into consideration. The relative index of operational wear resistance of the machined surface, which is characterized by the use of different variants of the structure and parameters of this surface treatment, depends on the microtopographic state of the surface layer and the presence of cutting-induced residual stress.

3. On the example of the stepped ejector pin for die casting mold, it was proved that the wear resistance of the functional surface increases by approximately 14% as a result of the change in the structure of the manufacturing process from abrasive machining (grinding) to edge-cutting machining (hard turning by means of a tool with the Tungsten Carbide insert). This example confirms the above theoretical assumptions.

Manuscript received by Editorial Board, January 19, 2020;
final version, April 01, 2020.

References

[1] V. Stupnytskyy and I. Hrytsay. Computer-aided conception for planning and researching of the functional-oriented manufacturing process. In: Tonkonogyi V. et al. (eds), *Advanced Manufacturing Processes*, part of the *Lecture Notes in Mechanical Engineering*, pages 309–320, Springer, Cham, 2020. doi: 10.1007/978-3-030-40724-7_32.

[2] J.P. Davim. *Surface Integrity in Machining*. Springer, London, 2010. doi: 10.1007/978-1-84882-874-2.

[3] W.E. Eder. Theory of technical systems – educational tool for engineering. *Universal Journal of Educational Research*, 4(6):1395–1405, 2016. doi: 10.13189/ujer.2016.040617.

[4] R.M. Rangan, S.M. Rohde, R. Peak, B. Chadha, and P. Bliznakov. Streamlining product lifecycle processes: a survey of product lifecycle management implementations, directions, and challenges. *Journal of Computing and Information Science in Engineering*, 5(3):227–237, 2005. doi:10.1115/1.2031270.

[5] F. Demoly, O. Dutartre, X.-T. Yan, B. Eynard, D. Kiritsis, and S. Gomes. Product relationships management enabler for concurrent engineering and product lifecycle management. *Computers in Industry*, 64(7):833–848, 2013. doi: 10.1016/j.compind.2013.05.004.

[6] V. Stupnytskyy. Computer aided machine-building technological process planning by the methods of concurrent engineering. *Europaische Fachhochschule: Wissenschaftliche Zeitschrift, ORT Publishing*, 2:50–53, 2013.

[7] A.I. Dmitriev, A.Yu. Smolin, V.L. Popov, and S.G. Psakhie. A multilevel computer simulation of friction and wear by numerical methods of discrete mechanics and a phenomenological theory. *Physical Mesomechanics*, 12(1-2):11–19, 2009. doi: 10.1016/j.physme.2009.03.002.

[8] T.R. Thomas. *Rough Surfaces*, 2nd edition. Imperial College Press, London, 1998. doi: 10.1142/p086.

[9] G. Straffelini. *Friction and Wear: Methodologies for Design and Control*. Springer, Cham, 2015. doi: 10.1007/978-3-319-05894-8.

[10] H. Aramaki, H.S. Cheng, and Y. Chung. The contact between rough surfaces with longitudinal texture – part I: average contact pressure and real contact area. *Journal of Tribology*, 115(3):419–424, 1993. doi: 10.1115/1.2921653.

[11] Yu A. Karpenko and A. Akay. A numerical model of friction between rough surfaces. *Tribology International*. 34:531–545, 2001. doi: 10.1016/S0301-679X(01)00044-5.

[12] N.B. Dyomkin. Calculation and experimental study of rough contact surfaces. In *Proceedings of Science Conference "Contact Problems and Their Engineering Applications"*, pages 264–271, Moscow, 1969.

[13] J. Luo, Y. Meng, T. Shao and Q. Zhao, (eds). *Advanced Tribology: Proceedings of CIST2008 & ITS-IFToMM-2008*. Beijing, China, 2008; Spriner, 2010. doi: 10.1007/978-3-642-03653-8.

[14] H. Hirani. *Fundamentals of Engineering Tribology with Applications*. Cambridge University Press, 2016.

[15] B. Bhushan. *Introduction to Tribology*. John Wiley & Sons, 2013.

[16] K.C. Ludema. *Friction, Wear, Lubrication. A Textbook in Tribology*. CRC Press, 1996.

[17] B.N.J. Persson. *Sliding Friction: Physical Principles and Applications*. Springer Science & Business Media, 2013.

[18] N.B. Dyomkin. *Contacting of Rough Surfces*. Moskow: Nauka, 1970. (in Russian).

[19] J.A. Greenwood and G. Williamson. Contact of nominally flat surfaces. In *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 295(1442):300–319, 1966. doi: 10.1098/rspa.1966.0242.

[20] S. Andersson and U. Olofsson. Simulation of plastic deformation and wear of a rough surface rubbing against a smooth wear resistant surface. In *Proceedings of the 10th International Conference on Tribology*, Bukharest, Romania, 2007.

[21] A. Ishlinsky and F. Chernousko. *Advances in Theoretical and Applied Mechanics*. Moskow: Mir, 1981.

[22] K. Hill. *The Matematical Theory of Plasticity*. Clarendon Press, Oxford, 1998.

[23] L.I. Sedov (ed.). *Foundations of the Non-Linear Mechanics of Continua*, volume 1 of *International Series of Monographs in Interdisciplinary and Advanced Topics in Science and Engineering*, 1966. doi: 10.1016/C2013-0-07842-5.

[24] A. Chmiel. Finite element simulation methods for dry sliding wear. M.Sc. Thesis, Air Force Institute of Technology. Wright-Patterson Air Force Base, Ochio, USA, 2008.

[25] M.W. Fu, M.S. Yong, and T. Muramatsu. Die fatigue life design and assessment via CAE simulation. *The International Journal of Advanced Manufacturing Technology*, 35(9–10): 843–851, 2008. doi: 10.1007/s00170-006-0762-5.

[26] I.V. Kragelsky, M.N. Dobychin, and V.S. Kombalov. *Friction and Wear: Calculation Methods*. Pergamon Press, Oxford, 1982.

[27] D.R. Askeland. *The Science and Engineering of Materials*. 3rd edition.: Springer Science & Business Media, Oxford, 1996. doi: 10.1007/978-1-4899-2895-5.

[28] V.P. Astachov. *Tribology of Metal Cutting*, volume 52 of *Tribology and Interface Engineering Series*. Elsevier Science, Amsterdam, 2006. doi: 10.1016/s0167-8922(06)x8001-x.

[29] V. Stupnytskyy. A generalized example of structural and parametric optimization of functionally-oriented process. *Bulletin of the National Technical University "KhPI". Series: Techniques in a machine industry*. 42(1085):116–130, 2014.

[30] Z. Nazarchuk, V. Skalskyi, O. Serhiyenko. *Acoustic Emission. Methodology and Application*. Springer, Cham, 2017. doi: 10.1007/978-3-319-49350-3.

[31] V. Stupnytskyy and I. Hrytsay I. Simulation study of cutting-induced residual stress. In: Ivanov V. et al. (eds), *Advances in Design, Simulation and Manufacturing II*. DSMIE 2019, part of *Lecture Notes in Mechanical Engineering*, pages 341–350, 2020. doi: 10.1007/978-3-030-22365-6_34.

[32] Y. Kudryavtsev and J. Kleiman. Ultrasonic technique and device for residual stress measurement. In T. Proulx (ed.), *Engineering Applications of Residual Stress*, volume 8 of *Conference Proceedings of the Society for Experimental Mechanics Series*. Springer, New York, 2011. doi: 10.1007/978-1-4614-0225-1_8.