Definition of the Parameters of Surface Layer Based on Functionality of Parts

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Abstract. The problem of increased reliability of parts is solved in the direction of obtaining the characteristics of their surface layer, providing the highest possible wear resistance. Tolerances on the accuracy of the machine, set on the basis of its functionality, are divided into tolerances for the manufacture of the machine and wear tolerances. In order to increase the reliability of products, they strive for the greatest possible tolerance for wear, increasing the accuracy of parts manufacturing. As a result, the costs of manufacturing the machine unnecessarily increase. The dependence of the rate of wear of parts on the roughness and hardness of their surfaces is extreme; therefore, the task of determining the parameters of the surface layer of the parts is optimization. The use of the wear rate of rubbing surfaces is justified as an optimization criterion. The technique and algorithm for assigning the parameters of the surface layer, providing a minimum rate of wear of the mating surfaces are presented. To solve this problem, a random search method was used. A method for calculating the tolerances for the manufacture and wear of mated parts operating under friction conditions is proposed.

1 Introduction

Improving the operational reliability of machines is one of the main problems of modern engineering. As shown by the statistical analysis of machine failures [1, 2, 3, 4], one of the main reasons for the failure of machines is wear and tear of movable mates and working bodies under the influence of friction forces. In this regard, the actual task of mechanical engineering technology is to increase the wear resistance of parts.

It is established that the wear resistance of parts is determined by the physical and mechanical characteristics of the surface layers and their roughness, so the problem of improving the reliability of parts in most cases is solved in the direction of obtaining the quality characteristics of the surface layer, providing the highest possible wear resistance under these conditions.

However, the problems of improving the reliability of products, as a rule, are solved regardless of the tasks to ensure the specified accuracy. It is known, the tolerances on all indicators of accuracy of the machine, established on the basis of its functionality, are divided into tolerances for the manufacture of the machine and tolerances for wear. In most

cases, this division is made arbitrarily, on the basis of experimental data, and in order to improve the reliability of products they tend to the largest possible tolerance for wear, i.e. increase the accuracy of manufacturing parts. In combination with the highest possible wear resistance of parts, this leads to the fact that the life time of the product can significantly exceed the value set by the service purpose of the machine. As a result, the cost of production and operation of the machine unnecessarily increase.

It should be noted that tolerances for the manufacture and wear of parts should be assigned on the basis of the condition of equal strength of the parts, i.e. their values should be such that the life time of the parts were the same or a multiple of the minimum life time (T_{min}) of the machine, defined by its service purpose. In this case, the operating costs of the machine can be significantly reduced by reducing the cost of repairs.

Thus, the further increase in production efficiency requires the creation of a method, which allows assigning the parameters of the surface layer quality and dividing the total tolerances on the quality indicators of the machine, based on its official purpose.

2 Review of theoretical studies

It is known that with an increase in the tolerance for the manufacture of parts, the costs associated with the manufacture of the machine are reduced (Fig. 1) therefore, part of the tolerance allocated to wear parts must have a minimum value that provides a specified life time of the part. In this case, the tolerance for the manufacture of parts will have the highest permissible value. The machine will work for a specified period of time without repair (or with a specified number of repairs); therefore the cost of its operation will be close to the minimum, since in most cases the bulk of these costs are repair costs [3, 5].

Fig. 1. Dependence of the cost of manufacturing and operation of machines from tolerances to manufacture.

To ensure such a value of the tolerance for wear it is necessary in the manufacture of parts to obtain the roughness and physical and mechanical properties of their surfaces, providing the lowest possible under these conditions, the rate of wear V_w of the mating parts, that is the minimum thickness of the layer of material removed from the surfaces of parts per unit time during friction.

Studies have found that the dependence of the wear of parts on the roughness and hardness of their surfaces is extreme [6, 7, 8, 9]. The minimum wear rate of parts is achieved not at the highest hardness and the lowest roughness of the surfaces, but at some of their values, determined by the friction conditions, which are optimal. Therefore, the

problem of determining the parameters of roughness and quality of the surface layer of parts is optimization.

As previously stated, to reduce the cost of manufacture of details, it is necessary to strive to expand the tolerances for the manufacture TA_{Am} of parts, and, consequently, to the reduction of tolerances TA_{Aw} for wear. In this regard, the average wear rate of the interface is used as a criterion for finding the optimal parameters of the surface layer quality

$$V_w \rightarrow \min$$

as $TA_{Aw} = V_w \cdot T_{min}$.

As a rule, the materials of parts working on friction in a pair are selected so that one of the parts, that is easier to make or replace during repair, wears out. Therefore, with a sufficient degree of approximation it can be considered as the rate of wear of the pairing is equal to the wear rate of the part with lower hardness, or lower the value of the modulus of elasticity.

Currently, a large number of empirical and analytical dependences describing the relationship of wear resistance of parts with the parameters of their surface layer and operating conditions, providing a sufficiently high accuracy of the results are obtained [6-13], but these dependences are mostly of a particular nature and are suitable for certain types of mates.

The dependence of the wear rate of the mating parts on the control parameters determined by the contact conditions of the rubbing surfaces of the parts are the most universal.

Thus, according to [6], the wear rate at elastic contact

$$V_{el} = V \frac{C_1 \cdot P_a^{1+\beta t_y}}{\chi} \left(\frac{E}{1-\mu^2} \right)^{t_y - \beta t_y - 1} \left(\frac{k \cdot f}{C_2 \cdot \sigma_o} \right)^{t_y}, \quad (1)$$

where V is the velocity of the relative motion of surfaces;

$$k = 1,5 \sqrt{4(1 - \mu - \mu^2) + (1 - 2\mu)^2 / f^2}$$

E , μ , σ_o are modulus of elasticity, Poisson's ratio, the value of the yield strength of the material, kg/cm²; P_a is nominal pressure, kg/cm²; t_y is index of the friction fatigue curve in elastic contact; f is coefficient of friction; C_1 , C_2 , χ , β are coefficients depending on the characteristics of the roughness of the surfaces of friction parts.

During plastic contact

$$V_{pl} = V \frac{1}{2(v+1)} \cdot \sqrt{\frac{v}{2} \cdot \frac{R}{r b^{1/v}}} \cdot \left(\frac{P_a}{HV_{min}} \right)^\gamma \cdot \left[\frac{1}{\varepsilon_o} \sqrt{\frac{2R}{r b^{1/v}}} \cdot \sqrt{\frac{\sigma_o + 2f \cdot HV_{min}}{\sigma_o - 2f \cdot HV_{min}}} \right]^{t_n}, \quad (2)$$

where $v = v_1 + v_2$; $R = R_1 + R_2$; t_n is index of friction fatigue curve in plastic contact; HV_{min} and ε_o are the hardness of the material and its elongation.

$$r = \frac{r_1 r_2}{r_1 + r_2};$$

$$b = k_v b_1 b_2 (R_1 + R_2)^{v_1 + v_2};$$

$$\gamma = 1 + \frac{t_n + 1}{2v}.$$

When micro cutting

$$V_{mc} = V \sqrt{v \cdot \frac{R}{r b^{1/v}}} \cdot \left(\frac{P_a}{HV_{min}} \right)^{\frac{1}{2v} + 1} \cdot \frac{1}{2v + 1}. \quad (3)$$

In order to determine the type of contact, the contact stress criterion is used [6]

$$C_N = \frac{k_f p_a^\beta E^{1-\beta}}{c_2(1-\mu^2)^{1-\beta} \cdot \sigma_o \chi^{1/t_y}}. \quad (4)$$

If $C_N < 1$ contact stresses are less than the yield strength, and V_w is calculated by the formula (2) for elastic contacting. If the contact stresses exceed the yield strength ($C_N \geq 1$), it is necessary to check the absence of micro cutting [6]

$$\sqrt{2 \frac{R}{r b^{1/\nu}} \left(\frac{P_a}{HV_{min}} \right)^{1/\nu} \cdot \frac{1+k_f}{1-k_f}} \leq 1 - e^{-\varepsilon_o}. \quad (5)$$

If this ratio is satisfied, V_w is calculated by the formula (3) for plastic contact conditions. Otherwise, there is micro-cutting and the wear rate is determined by the formula (4).

The analysis of these dependences shows that the main parameters of the surface layer determining the wear rate of the mating parts are:

- v_1, v_2, b_1, b_2 – parameters of the curves of the reference surfaces of the conjugate parts, the first and second ones respectively;
- R_{max1} and R_{max2} – maximum height of irregularities of surfaces of the parts;
- r_1 and r_2 the average radius of the peaks of irregularities of surfaces;
- HV_1 and HV_2 – average hardness of the surfaces of parts.

These variables are taken as independent control parameters in solving this problem.

The service purpose of the parts is specified their shape, size, materials, minimum service life T_{min} , the average speed of their surfaces V , load, lubrication conditions, temperature. Knowing the material of the part and its shape, it is possible to determine the range of methods of processing this part and, consequently, the upper and lower limits of variation of control variables:

$$b_{imin} \leq b_i \leq b_{imax}; v_{imin} \leq v_i \leq v_{imax}; R_{imin} \leq R_i \leq R_{imax}; r_{imin} \leq r_i \leq r_{imax}; \\ HV_{imin} \leq HV_i \leq HV_{imax}. \quad (6)$$

3 Results and discussion

The algorithm for calculating the optimal quality parameters of the surface layer of parts is shown in Fig. 2.

The method of random search is used to solve this problem. Random values of control parameters are generated taking into account restrictions (6). Then the criterion (4) is calculated and, in the case of $C_N < 1$, the average wear rate V_w is calculated by the formula (1). In the case of $C_N \geq 1$, the condition (5) is checked. When this condition occurs, the calculation of the average wear rate V_w is realized by the formula (2), the failure – according to the formula (3). Next, the calculation result is compared with the previous value of the average wear rate V_w , and the smaller value of V_w is stored. As a result of the search of a large number of combinations of control parameters, the values of the quality characteristics of the surface layer are selected, providing a minimum wear rate of the interface.

In most cases, it is impossible to obtain the exact calculated values of the surface layer quality parameters during the machining process. Due to fluctuations in the quality of the material, allowance and other factors, the surface hardness and average height of the profile irregularities will fluctuate within some ranges of scatter ω_{HV} and ω_{Rz} . As a result, the value of the average wear rate of parts in a batch of parts will also vary from V_{wmin} to V_{wmax} .

Limiting the fluctuation of hardness and the height of the profile irregularities by tolerances T_{HV} and T_{Rz} , we can calculate the upper limit of fluctuations in the wear rate using one of the following formulas:

for elastic contact

$$V_{el\ ma} = V \frac{(C_1 + \Delta C_1) \cdot P_a^{1+\beta t_y}}{\chi + \Delta \chi} \left(\frac{E}{1-\mu^2} \right)^{t_y - \beta t_y - 1} \left(\frac{k \cdot f}{(C_2 + \Delta C_2) \cdot \sigma_o} \right)^{t_y}, \quad (7)$$

where ΔC_1 , $\Delta \chi$, ΔC_2 are the changes of the coefficients depending on the parameters of the curve of the reference surface in b and v , and the maximum height of the irregularities R . At the same time $R = 1,15R_z$ and $R_z = R_{z\ ext} \pm T_{Rz} / 2$;
 for plastic contact

$$V_{pl\ max} = V \frac{1}{2(v+1)} \cdot \sqrt{\frac{v}{2}} \cdot \frac{R_{ext} \pm T_{R/2}}{r b^{1/v}} \cdot \left(\frac{P_a}{HV - T_{HV}} \right)^Y \cdot \left[\frac{1}{\varepsilon_o} \sqrt{\frac{2(R_{ext} \pm T_{R/2})}{r b^{1/v}}} \cdot \sqrt{\frac{\sigma_o + 2f \cdot (HV - T_{HV})}{\sigma_o - 2f \cdot (HV - T_{HV})}} \right]^{t_n}; \quad (8)$$

Fig.2. Algorithm for calculating the optimal parameters of the surface layer quality of parts.

when micro cutting

$$V_{mc\ ma} = V \sqrt[3]{\nu \cdot \frac{R_{ext} \pm T_R/2}{r b^{1/\nu}}} \cdot \left(\frac{P_a}{HV - T_{HV}} \right)^{\frac{1}{2\nu+1}} \cdot \frac{1}{2\nu+1}. \quad (9)$$

When calculating $V_{w\ max}$ the fluctuation of the two control parameters of the five ones – hardness T_{HV} , and the average height of irregularities T_{Rz} was taken into account. This is due to the fact that the design and manufacture of parts are set and controlled mainly these parameters of the surface layer quality. The remaining three parameters – the parameters of the curve of the reference surface ν and b and the radius of the peaks of irregularities of the irregularities r , are provided mainly by the method of processing the surface of the part, and, at present, no reliable method of controlling them has been found. In known $V_{w\ min}$ and $V_{w\ max}$ we can calculate the values of manufacturing tolerances $TA_{\Delta m}$ and tolerances for wear of the parts.

So, according to Fig. 3

$$TA_{\Delta w} = V_{w\ max} \cdot T_{min} \text{ and } TA_{\Delta m} = TA_{\Delta} - TA_{\Delta w} \quad (10)$$

or

$$TA_{\Delta m} = TA_{\Delta} - V_{w\ max} \cdot T_{min}. \quad (11)$$

In this case, the value of the actual life time of the mate will fluctuate within the scattering range

$$\omega_T = \frac{TA_{\Delta}}{V_{w\ min}} - T_{min}. \quad (12)$$

Fig. 3 Scheme for the calculation of tolerances for wear and manufacture of parts.

A_{min} and A_{max} are the minimum and maximum clearances in the mate specified by the service purpose of the product;

$A_{min\ m}$ and $A_{max\ m}$ are the minimum and maximum clearances in the mate for manufacturing of the parts

Calculations according to the proposed method require a large amount of initial data, which significantly increases the time to solve the problem. To reduce the time of

preparation for calculations, the so-called input algorithm was developed, which allows from a small amount of input data to form a complete array of source information.

Below an example of finding the optimal quality parameters of the surface layer and determining tolerances for the manufacture and wear for the mating parts "sleeve–piston" of a hydraulic pump is shown. Piston material is steel hardened, material of the sleeve is bronze.

With the existing technology of manufacturing these parts, the actual roughness of their surfaces is Rz 1,6–0,8 micrometers. The highest value of the clearance in the coupling allowed by official designation of the pump TA is not more than 0.025 mm, the manufacturing tolerance TA_m is 0.015 mm, wear tolerance pairing TA_w equal to 0,010 mm. With these parameters, the life time of pairing is 3500–3800 hours [15].

In determining the optimal parameters of the quality of the surface layer of the interface parts according to the developed algorithm (Fig. 2) the following values are obtained:

- for the sleeve $b_1 = 2.001$; $v_1 = 1.279$; $Rz_1 = 0.17 \mu\text{m}$; $r_1 = 0.679 \text{ mm}$; $HV_1 = 180 \text{ kg/mm}^2$ (176.4 MPa).

- for the piston $b_2 = 0.854$; $v_2 = 1.336$; $Rz_2 = 0.94 \mu\text{m}$; $r_2 = 0.385 \text{ mm}$; $HV_2 = 640 \text{ kg/mm}^2$ (627.2 MPa).

These quality parameters of the surface layer of the parts ensure the minimum possible wear rate of the mate $V_w = 0.1295 \cdot 10^{-5} \text{ mm/hour}$ in elastic contact.

Setting the tolerances to the maximum height of irregularities $T_{R1} = 0.017 \mu\text{m}$ and $T_{R2} = 0.094 \mu\text{m}$, and the amount of hard surfaces $T_{HV1} = 5 \text{ kg/mm}^2$ and $T_{HV2} = 20 \text{ kg/mm}^2$, the formula (7) defines the upper value of the wear rate of the pairing $V_{w \max} = 0.1546 \cdot 10^{-5} \text{ mm/hour}$.

Setting lifetime of the mate $T_{\min} = 4000$ hours, the tolerance for the wear defines according to the formula (10)

$$TA_w = 4000 \times 0.1546 \times 10^{-5} = 0.0062 \text{ mm},$$

and the tolerance for the manufacture of parts is

$$TA_m = 0.025 - 0.0062 = 0.0188 \text{ mm}.$$

Thus, due to the optimal quality of the surface layer in the processing of parts, all other things being equal, the tolerance for wear of the interface is reduced by 1.3–1.4 times, and, accordingly, the tolerance for their production increases, which reduces the costs associated with the manufacture of parts.

In the case where the magnitude of the tolerances in manufacture and wear remain the same, i.e., $TA_w = 0.01 \text{ mm}$, $TA_m = 0.015 \text{ mm}$, the life time of this pairing, at optimum quality parameters of the surface layer will be

$$T_{\min} = 0.01 / (0.1546 \times 10^{-5}) = 6468 \text{ hours}.$$

4 Conclusion

Thus, while ensuring the optimal parameters of the surface layer quality and the previous distribution of tolerances on the product quality indicators, the life time of the interface increases by 25–30%.

The experience of similar calculations with the help of the computer program developed on the basis of the proposed algorithm has established that the application of the proposed method allows to reduce the time spent on the design of technological processes for processing parts working under conditions of wear by sliding friction by 3–5 times.

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