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Duplex Scheme of the Technological Impact of the Provision of Operational Properties of a Hardened Large Module Gears

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Abstract: The two-level circuit of technological influence of providing of operating properties of hard-tempered large module gears is offered on basis division of tasks of technologist and designer with regulation of complex parameters on each of these stages and subsequent decision of task of choice of optimum value of operating properties.

Keywords: Two-level circuit, technological influence, operating properties, large module gears

1. Introduction

One of the methods for solving the problem of multi-criteria optimization of the technological impact on ensuring the operational properties (OP) of the surfaces of hardened large-module gears in mechanical engineering is considered [1, 2, 3, 4, 5, 11]. The system of complex parameters, justification of their choice, elements of functional and cost analysis for ensuring the operational properties of the surface of hardened large-module gears and probabilistic evaluation of its gear processing methods are presented [6, 7, 8, 9, 10].

2. Problem Statement

Currently, the surface quality is regulated by the parameters in accordance with ISO 1101:2004 and ISO 4287-1997. At the same time, as scientific research shows [1, 12, 13, 17, 22, 24, 25], technological support is most effectively carried out with the help of complex parameters of the surface state. Their choice, especially during production, reveals new reserves for reducing the cost and improving the quality of gears.

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The duplex scheme of technological impact on the provision of OP is based on the separation of the tasks of the technologist and the designer with the regulation of complex parameters at each of these stages. And then with the subsequent solution of the problem of choosing the optimal value of the OP.

The structure of the model is proposed, on the basis of which the method and modes of surface treatment of hardened large-module gears are selected, while providing several OP, while preserving traditional approaches to surface regulation. It includes the following steps:

1. Determination of the structure of the OP, which are applied to hardened large-module gears and the establishment of formal numerical and boundary values;
2. Selection of complex parameters of working involute surfaces, their theoretical justification, calculation of their numerical values at the stage of design or technological development and their regulation;
3. Assignment of possible methods for providing complex parameters at the stage of selecting the technological method of tooth processing;
4. Functional cost analysis (FCA) of processing methods from the point of view of joint provision of the necessary OP values;
5. Calculation of the modes and selection of the optimal technology of tooth processing.
6. Forecasting the quality assurance of surface characteristics and, as a result, hardened large-module gears when choosing this technological support [14, 15, 16, 18].

3. Proposed Solution

When designing, an important task is to establish the OP requirements for hardened large-module gears. In [1], it is noted that it is necessary to establish limiting OP, which determine the reliability and accuracy of gears [17, 19, 20, 21]. These and other questions are considered when solving the problem in blocks 1-4 (Fig. 1), and attention should be paid to their numerical values and the rationality of their purpose.

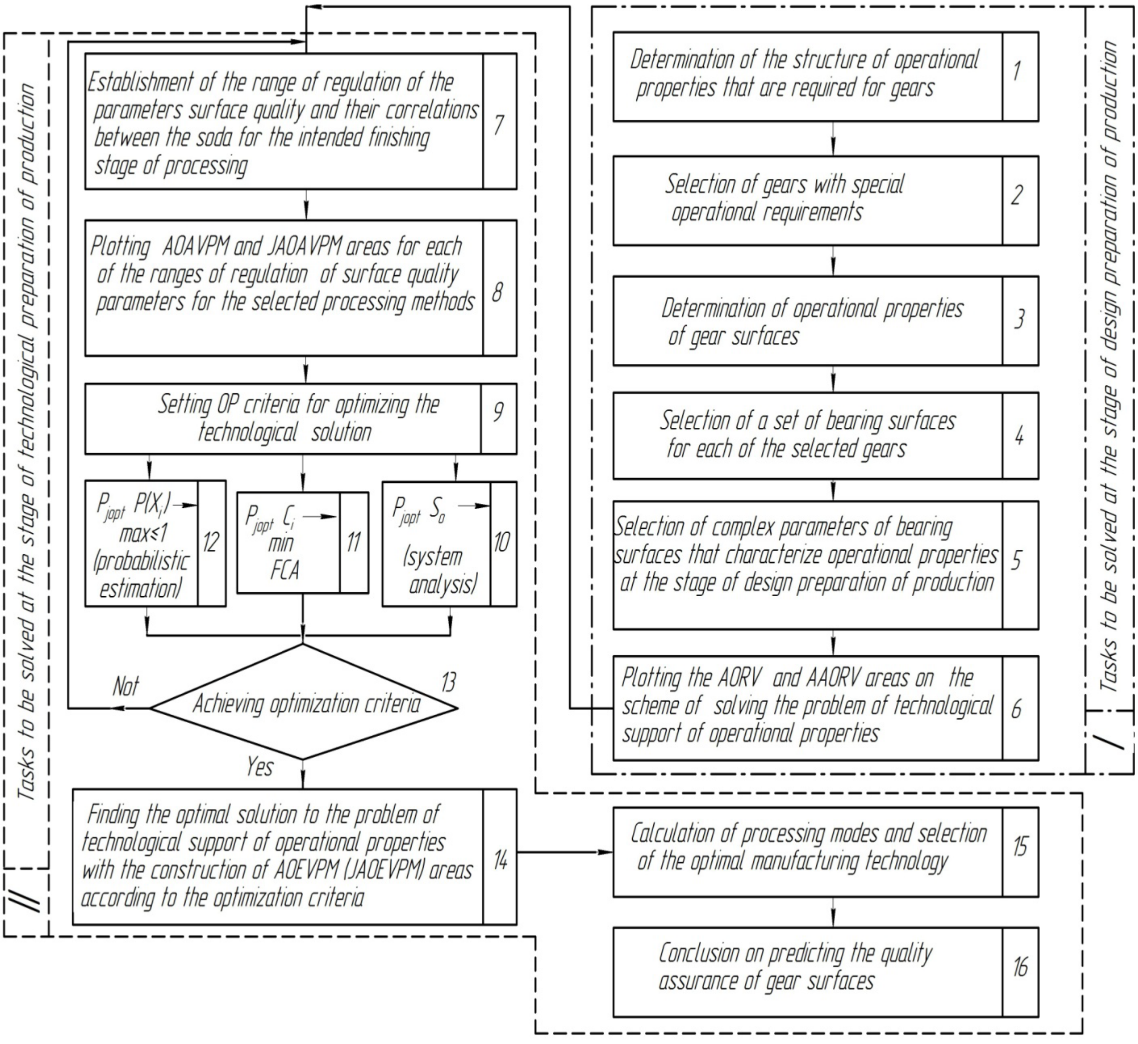

Fig. 1 - Structure of modeling of technological support of OP surfaces of hardened large-module gears

At the stage of design preparation of production, the selection of complex parameters that characterize the OP of the surfaces of hardened large-module gears can be made using Table 1.

Table 1 - Complex parameters (CP) used in the technological support of OP surfaces of hardened large module gears during normal wear

Name of the surface	**CP**	**Technological value of the parameters**	**Calculation and design value of parameters**
Working in the conditions of growing active surfaces	C_x	$\frac{H_p \cdot W_p \cdot (R_p)^4}{(S_m)^6 \cdot (K^{\mid})^{12}}$	$3375 \cdot \left[\frac{\sigma_T \cdot E}{\pi \cdot (1-\mu^2)}\right]^3 \cdot \left(\frac{10 \cdot J_{П} \cdot \lambda}{\chi \cdot P}\right)^6$
Working in conditions of peeling of the surface layers of the teeth	W	$\left[\frac{R_p \cdot W_p \cdot H_p}{(K^{\mid})^{0,5}}\right]^{\frac{1}{3}}$	$\left[\frac{\sigma_T \cdot J^6_{ПЛ}}{1.7 \cdot \mathrm{P}}\right]^{\frac{1}{6}}$
Working in conditions of broken teeth	B	$\frac{R_a^2 \cdot K^{\mid}}{W_z \cdot H_{\max}}$	$\frac{P}{A \cdot \sigma_T}$
Operating under conditions of abrasive tooth wear	I	$\frac{R_a}{S_m \cdot K^{\mid}}$	$\frac{2 \cdot \pi \cdot \sigma_T \cdot (1-\mu^2)}{E}$
Working in conditions of plastic deformations of teeth	D	$\frac{K^{\mid} \cdot S_{mw}^{0,4} \cdot R_a}{W_a^{0,2} \cdot S_m \cdot t_m}$	$\frac{\gamma^{0.2}}{13.5} \cdot \left[\frac{\sigma_{-1Д}}{\sigma_{-1}} - 1\right]$
Operating under jamming conditions	C_M	$R_p + W_p + H_p$	$\Delta - 2 \cdot 10^3 \cdot \frac{M}{\pi dlf} \cdot \frac{C}{E}$

In table 1, H_p – height of smoothing macro profile; W_p – height smoothing profile waviness; R_p – distance from the line projections to midline; S_m – average step irregularities; $K^{\mid}$ - coefficient of strengthening of the surface layer; H_{max} is the maximum height of macro profile; t_m – relative bearing surface irregularities on the level of the median line; σ_T – yield strength; E – Young's modulus; μ is the Poisson's ratio; $J_{ПЛ}$ – deformation component; λ – coefficient taking into account the influence of surface residual stresses on the number of loading cycles; χ –coefficient; P – specific pressure on the surface; γ – dimensionless coefficient depending on the ratio σ_T/σ_B; $\sigma_{-1Д}$ – endurance limit of the part; σ_{-1} – endurance limit of not hardened design; C – stiffness coefficient; f – friction coefficient; M, d and l – connection parameters: torque, applied to the pair, the diameter and length of conjugation, respectively.

At this stage, the complex parameter is assumed to be equal to the value of the parameter during normal wear and is determined only by the physical and mechanical properties and operating conditions. This problem is solved in block 5 (Fig. 1).

In Table 1, the values of the complex parameters (CP) are determined by the equality of the technological values of the parameters and the design values of the parameters Cx, W, B, I, D and CM, which are set by the designer and can vary from 0,00225 to 0,15 depending on the requirements of the technological processing conditions.

The plotting of the area of regulated values of OP (AORV) can be carried out using applied mathematics [13, 18, 22, 23]. When providing several OP, it is necessary to build a separate AORV area for each of them and determine the appropriate area of regulated OP values (AAORV) by intersecting these areas with each other. This area will include all the OP, the achievement of which, set the designer before the technologist. In fact, this is the output of the designer, technologist required as input data for technological support of OP of coarse-grained surface hardened gears (block 6, Fig. 1).

To solve the problem of optimization of technological support OP is necessary to determine the scope options AORV (AAORV):

$$S_{Pij} = \left(X_{iPij\max} - X_{iPij\min}\right) \cdot \left(Y_{jPij\max} - Y_{jPij\min}\right) \tag{1}$$

$$S_{P\Sigma ij} = \left(X_{iP\Sigma ij\max} - X_{iP\Sigma ij\min}\right) \cdot \left(Y_{jP\Sigma ij\max} - Y_{jP\Sigma ij\min}\right) \tag{2}$$

Where, $X_{iP\Sigma ijmax}$, $X_{iP\Sigma ijmin}$ are the minimum and maximum values of the surface quality parameters that are the limiting functions of the region $P_{\Sigma ij}$ (AORV, AAORV); $Y_{jP\Sigma ijmax}$, $Y_{jP\Sigma ijmin}$ are the minimum and maximum values of the complex parameters of the surface state that reflect its OP;

The task of the technologist, at the first stage, is to pre-establish the final stage of surface tooth treatment using a graph model of the technological process, using instead of the arithmetic mean deviation of the *Ra* profile and the *IT* accuracy quality, the complex parameter and the IT accuracy quality.

Also, its task is to establish the range of surface quality regulation at the final stage of tooth processing and to identify correlations between these parameters. All these tasks are solved in block 7 (Fig. 1).

$$R_a = f(R_z);\ R_{max} = \varphi(R_z);\ t_m = \psi(S_m);\ t_{mw} = \xi(S_{mw});\ W_p = \chi\ (W_z). \tag{3}$$

$$W_z = F(S_{mw});\ W_z = \zeta(W_{max});\ H_p = r(H_{max});\ \sigma = g(h_\sigma). \tag{4}$$

Where, $f,\ \varphi,\ \psi,\ \xi,\ \chi,\ F,\ \zeta,\ r,\ g$ are the correlation functions of the surface layer parameters, σ is the value of the residual stresses on the surface, h_σ is the depth of the residual stresses on the surface, the other parameters are shown in Table 1.

Next, you should build a system optimization scheme (Block 8, Fig. 1) technological support of OP (Fig. 2) definition of the AORV, AAORV areas region achievable values of OP treatment method (AOAVPM), a joint region AOAVPM (JAOAVPM), the effective values of the method of treatment (AOEVPM), a joint region of AOEVPM (JAOEVPM). Figure 3 shows a diagram of the functional cost analysis (FCA) problem and processing methods from the point of view of jointly providing the necessary OP values.

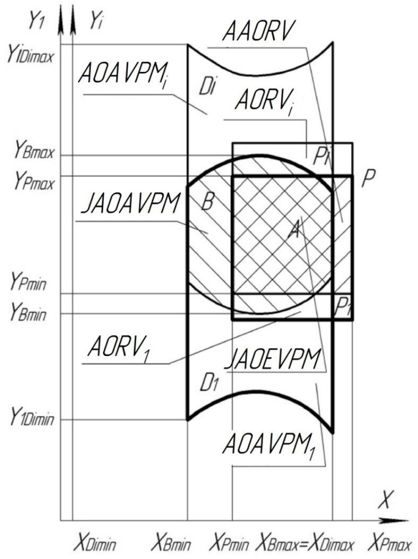

Fig. 2 - Scheme of system optimization for providing multiple OP

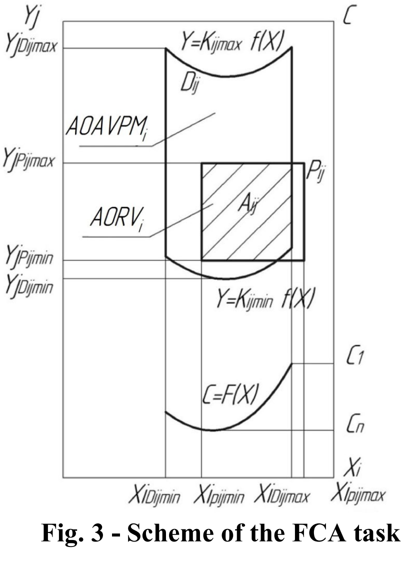

Fig. 3 - Scheme of the FCA task

$$S_{Dij} = \left(K_{ij\max} - K_{ij\min}\right) \cdot \int_{X_{iPij\min}}^{X_{iDij\max}} f\left(X_i\right) dX_i \tag{5}$$

$$S_{D\Sigma ij} = \sum_{\psi=1}^{e} \left[K_{BD\Sigma ij} \cdot f_{BD\Sigma ij}\left(X_i\right) - K_{HD\Sigma ij} \cdot f_{HD\Sigma ij}\left(X_i\right)\right]_e \tag{6}$$

$$S_{A\Sigma ij} = \sum_{\psi=1}^{t} \left[K_{BA\Sigma ij} \cdot f_{BA\Sigma ij}\left(X_i\right) - K_{HA\Sigma ij} \cdot f_{HA\Sigma ij}\left(X_i\right)\right]_t \tag{7}$$

Where, ψ is the number of intersected sets; X_i is the values of the *i*-th parameter, the values of which are regulated and plotted on the abscissa axis (the surface quality parameter); K_{ij} is the coefficient reflecting the influence of complex parameters not considered by *j* for the *i*-regulated surface quality parameter [2]. $f_{HD\Sigma ij}(X_i)$, $f_{BD\Sigma ij}(X_i)$ - the function of the lower and upper curve reduced to the *j* indicator, limiting the area $D_{\Sigma ij}$; $f_{HA\Sigma ij}(X_i)$, $f_{BA\Sigma ij}(X_i)$ - the reduced function of the lower and upper curve, limiting the area $A_{\Sigma ij}$ by the regulated parameter; $K_{BD\Sigma ij}$, $K_{HD\Sigma ij}$ - values of the coefficients reflecting the influence of other parameters in the upper and lower functions to restrict the $D_{\Sigma ij}$; $K_{BA\Sigma ij}$, $K_{HA\Sigma ij}$ - values of the coefficients taking into account the influence of other parameters in the upper and lower functions to restrict the $A_{\Sigma ij}$; *e* - number of educated sets JAOAVPM; *t* - the number of educated sets of JAOEVPM.

To optimize the technological support of the OP, when regulating two surface quality parameters simultaneously, the correlations between them (3) and (4) are taken into account. This problem should be solved not in a two-dimensional coordinate system, but using spatial modeling. As an example, we selected the OP software using a complex parameter for surfaces operating under linear wear conditions (Table 1). Graphically, the AOAVPM region can be constructed using the MathCAD mathematical package (Fig. 4 and Fig. 5). In Fig. 4, the gear wheel processing section with a worm modular milling cutter is used when adjusting Sm and Ra with high-speed counter gear milling.

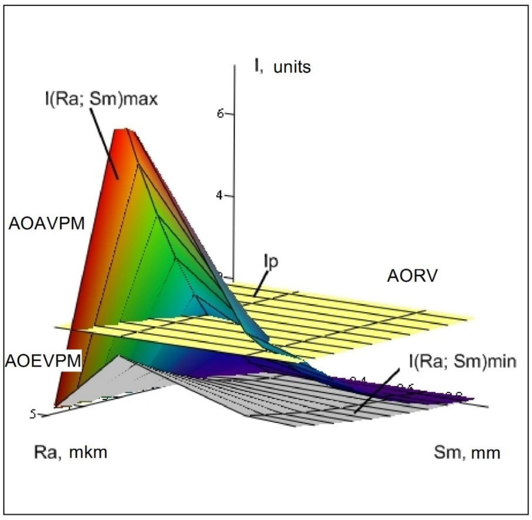

Fig. 4 - The AOAVPM area for gear processing in the S_m and *Ra* regulation

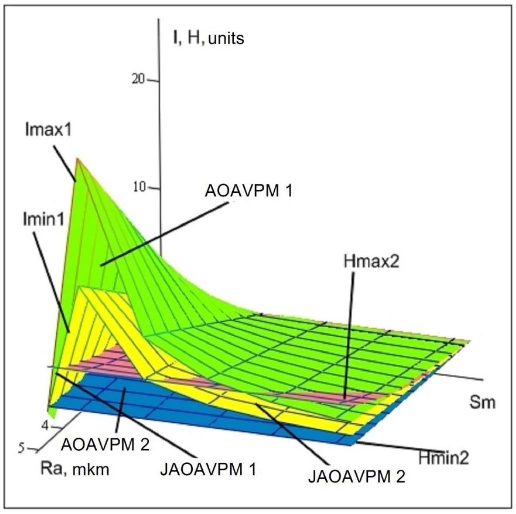

Fig. 5 - Region JAOAVPM in regulating the parameters *Sm* and *Ra*

Volume of the AOAVPM area:

$$V_{\text{AOAVPM}} = \iint_{D_1} \frac{R_a}{S_m \cdot K^{|}_{\max}} dR_a dS_m - \iint_{D_1} \frac{R_a}{S_m \cdot K^{|}_{\min}} dR_a = \int_{R_a^{\min}}^{R_a^{\max}} \left[\frac{R_a}{K^{|}_{\max}} \cdot \left(\ln \frac{K_{f2} \cdot \sqrt[m]{R_a}}{K_{f1} \cdot \sqrt[n]{R_a}} \right) \right] dR_a - \int_{R_a^{\min}}^{R_a^{\max}} \left[\frac{R_a}{K^{|}_{\min}} \cdot \left(\ln \frac{K_{f2} \cdot \sqrt[m]{R_a}}{K_{f1} \cdot \sqrt[n]{R_a}} \right) \right] dR_a \quad (8)$$

Where, V_{AOAVPM} is the volume of the AOAVPM region; K_{fi} is the correlation coefficient; *n, m* are the exponents of the degree.

Using the criteria of optimization of technological support of OP (Fig. 1) you need to determine whether this method of treatment at the finishing stage of maximal condition values of the area of JAOEVPM from all the selected methods of the minimal costs (FCA) and the maximum value of the probability P(A) for a given processing method (units 9 – 14, Fig. 1). If not, you should go back to the definition of finishing processing or handling method in the final stage, as well as change the quality setting surface (block 7, Fig. 1).

The DORV area is denoted as A, AOAVPM – D, AOEVPM – B (Fig. 3). Using set theory, the authors formulate statements that reflect the criteria for optimizing the technological support of several OP surfaces of parts:

1. For each method of tooth processing (MOTP) at the final stage, there is a limited set (set) of areas D, for each of which there is a cost function C_i;
2. From the set of areas in, there will be an AOEVPM area (one) that will meet three criteria:
2.1. Will have the maximum value of the intersection area of AOAVPM and DORV (S_D);
2.2. Will have the minimum value of the cost function C_i;
2.3. Will have the maximum probability of providing OP for this MOTP;
3. This area of the AOEVPM, which meets the criteria 2.1, 2.2 and 2.3, will be optimal from the point of view of the technological support of the OP.

Mathematically, this can be expressed as:

1. $\forall MO \exists D \exists C$; 2.1. $\exists_B B_{joon\,.} S_D \to \max$;

D = {D_1, D_2, D_3, … , D_i}; 2.2. $\exists_B B_{joon\,.} C_i \to \min$;

C = {C_1, C_2, C_3, …, C_i}; 2.3. $\exists_B B_{joon\,.} P_i(A) \to \max$;

$C_i = F(x_i)$; $A \cap D = B$; $B = \{B_1, B_2, B_3, \ldots, B_j\}$; $B_{onm} \in B$.

The JAOEVPM area is the output information required for performing the FCA and probabilistic evaluation (PE) of the tooth processing method. Not only its area, but also its position in the coordinate system, plays an essential role in ensuring the OP of the surface. Since the projection of extremes from this area on the cost function determines the amount of costs for this processing method. And the position of the distribution curve of the surface quality parameters in relation to the area JAOEVPM determines the probability of providing the OP surface with the selected method of tooth processing.

4. Results and Discussion

1. The surface quality parameters R_p, S_m, Ra, etc. are a function of a random variable, these arguments relate to the range of achievable values of the complex parameter for the considered method of tooth processing D, and the range P, is equally probable.
2. To ensure operational properties, when setting a limited set of surface quality parameters, the probability for the selected gear treatment method is determined as follows

$$P(R_{ij}) = \prod_{i=1}^{n} P(R_i), \tag{9}$$

where, $P(R_i)$ is the probability of ensuring operational properties when regulating the i-th parameter of the state of the surface layer.

3. The purpose of the modes of gear processing, which provides the specified operational properties (Block 15, Fig. 1). To determine the processing modes, the empirical equations of the parameters of the state of the surface layer are used:

$$(R_a, R_p, S_m) = f(S;V;r;\gamma), \tag{10}$$

where, S – feed, mm/rev.; V – cutting speed, m/min.; r and γ – parameters of the cutting tool, the radius of the cutting edge and the front angle, respectively.

To ensure operational properties, optimization criteria are used in the form of inequality (Table. 1): [2, 5, 9, 16]

$$[P] \le P, \tag{11}$$

where, P – the design value of the complex parameter; $[P]$ - the value of the complex parameter, achievable by surface treatment.

5. Conclusions

1. The issues of ensuring the quality of hardened large-module gears in their manufacture due to the provision of OP of their surfaces are considered.
2. The algorithm of two-stage provision of OP of surfaces on the basis of application of complex parameters of a state of a surface and its multicriteria optimization is developed.
3. The criteria for optimizing the technological support of several OP surfaces of hardened large-module gears using complex parameters of their condition are formulated.
4. Recommended parameters for optimizing the technological support of OP surfaces of hardened large-module gears.
5. The results of the work were tested in the machining of hardened large-modulus gears 6, 7 and 8 accuracy standards according to ISO 1328-1–2017.

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