Power Consumption Optimization in Tooth Gears Processing

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Abstract. The paper reviews the issue of optimization of technological process of tooth gears production of the power consumption criteria. The authors dwell on the indices used for cutting process estimation by the consumed energy criteria and their applicability in the analysis of the toothed wheel production process. The inventors proposed a method for optimization of power consumptions based on the spatial modeling of cutting pattern. The article is aimed at solving the problem of effective source management in order to achieve economical and ecological effect during the mechanical processing of toothed gears. The research was supported by Russian Science Foundation (project No. 17-79-10316).

1. Introduction
In the current conditions of global competition and modern state of ecology, it is hard to overestimate the impact of power engineering on the all fields of man's activity. Consequently, there is a problem of effective energy source management in order to achieve both economic and ecological effects. The distinguishing characteristic of engineering industry is a high level of power consumption of manufactured items. The share of the energetic component in the manufacturing cost of production made on the machine-building enterprises amounted to 25% [1, 2, 3]. In Russian's machine-building enterprises, 450-600 kilowatt-hours of electric energy are spent for production of 1 ton of facing. Analogous production made in the industrialized Europe countries consumes is 1.5-2 times smaller amount of energy [4]. Main of the reason for it is that the energy intensity and metal removal criteria’s are applied along with the major criteria (cost value, accuracy, manufacturing capability) during the developing the technological processes in the Germany, France and other countries [5, 6, 7].

The major part of shaping parts (more than 2/3 of the total items) account for gear wheels, profile and other parts of complex shape, and the accumulated park of technological equipment does not allow to reduce the production operating time. Moreover, the park is constructed in 80-yes, in the era of cheap energy. Processing of the surfaces can take up to 70% of normal time of item manufacturing.

Hence, increasing of energy efficiency of technological processes of tooth wheel machining by the optimization of energy costs is the urgent task of modern machinery production.

The aim of this work is to develop a method of determining the optimal parameters of the technological system (process conditions and design of the cutting tool) in which the desired quality of surfaces, cutting tool durability and productivity will be ensured by the minimum necessary amount of energy.

2. Optimization of energy cost in the processing of gear wheels
The problem of increasing of energy efficiency in general can be solved by reducing the energy losses in the cutting area, mechanical or electrical part of the equipment.

In the article, the option of the management of the energy efficiency of the process. Since the mechanical work performed by the cutting tool during each working stroke and determined the regularities of chip formation affects the load losses in transmission and determines the total amount of energy consumed by the machine engine.

There are a number of parameters, by which it is possible to evaluate the cutting process from the point of view of supply energy, in particular the specific energy of cutting process. The energy intensity
of the cutting process characterizes numerically the amount of energy expended by the cutting tool to the separation the unit volume of the shear layer in the chip form (a preliminary stage processing), or for the formation of a unit area of new item surface. The advantages of this index include its simple determination by both theoretical and experimental methods.

However, the energy intensity index is proportional to the cutting power, but the power is supposed to be constant during the whole operating stroke, which is rare and becomes true only for stationary cutting.

It is possible to use nondimensional parameter K, which is an energetic performance factor of cutting process, as integral characteristics of the efficiency of machining proposed:

\[ K = \frac{\Delta wV}{n_c A_c} = \frac{\Delta wV}{n_c \int_0^\tau N(\tau) d\tau} \]  

(1)

where \( \Delta w \) – energy intensity of processing material; \( V \) – the volume of treated material being exposed; \( n_c \) – the number of cycles of cutting power \( N(\tau) \) changing during the working cycle of the tool; \( A_c \) – cutting job during \( \tau_c \) one cycle of output variation.

Duration \( \tau_c \) of one cycle of the cutting power change refers to the time period of the working stroke or period of time during which there is a complete one-time change in cutting power at the transient mode.

Parameter K meets requirements established for criteria of optimality of technological processes. This indicator expresses the efficiency of the cutting process and thus has a physical meaning. It clearly described in a mathematical form. This form can be reduced to the objective function of the form \( K \rightarrow \max \); indicators of properties of processed and tool materials, geometric parameters of the tool and the shear layer, the elements of the cutting mode, the kinematics of the machining process are the arguments of the function.

However, if it is necessary to evaluate the energy efficiency of cutting processes of gear machining (gear shaping, gear milling, gear planing, etc.), expression 1 can not be used, since at each cycle of loading the tool can remove chips of various configurations, therefore, the cutting job will change. Expression 1 for description of efficiency of gear wheels processing will take the following form:

\[ K = \frac{\Delta wV}{\sum_{i=1}^n P_{zi}} \]  

(2)

Cutting job can be expressed through processing modes and workpiece parameters:

\[ K = \frac{60 \cdot 1020 b \Delta wV}{v^2 \sum_{i=1}^n P_{zi}} \]  

(3)

where \( b \) – gear face width; \( v \) – cutting speed; \( P_{zi} \) – axial cutting force.

3. Cutting force definition

The empirical approach is currently widely used to determine the cutting forces. The approach is based on the "Mechanistic Force Modelling". Method essentially consists in determining the specific forces per unit length of cutting blade and then summing the forces by all cutting edges involved in cutting.

Power for the processes of cutting by the tool with custom profile can be calculated using the method, when several edges are involved in the process of the chip removal. R. V. Anisimov calculated by this method the force produced by shaping the inner noninvolute gears [8]. According to this approach L. Berglind, D. Plakhontnik developed a model to calculate the cutting forces occurring during machining of an arbitrary configuration on the five-axis milling centers [9].

A disadvantageous feature of this approach is that the model has to be calibrated in order to refine adjustment factors in case of any changes (use of new processing modes, using a new cutting tool, etc.).
Calibration is implemented by means of complex experimental studies. The forecast error will be less than 5% [10] after calibration of the model.

Calculation of the specific forces is made first. According to [8] specific forces in tooth gears processing are defined as follows:
in the range of cut layer thickness from 0.01 to 0.5 mm
\[ \Delta P_z = \left( 1.7 \cdot 10^2 a^{0.9} + 4.3 - 9(\gamma + \Delta \gamma) \right)(\alpha - \Delta \alpha)^{-0.07} 9.8K_{Pz} \]
(4)
in the range of cut layer thickness from 0 to 0.01 mm
\[ \Delta P_z = (57 + 2210a)K_{Pz} \]
(5)
where \( a \) – thickness of cutting layer; \( \gamma \) – front angle of the instrument; \( \Delta \gamma \) – kinematic change of the front angle; \( \alpha \) – back angle of the tool; \( \Delta \alpha \) – kinematic change of the back angle;
\( K_{Pz} \) and \( K_{Py} \) – generalized correction factors which are equal to the product of the coefficients \( K_M \), \( K_{CCF} \), \( K_h \), and \( K_V \). These coefficients take into account the following factors: \( K_M \) – material; \( K_{CCF} \) – coolant-cutting fluid; \( K_h \) – tool wear; \( K_V \) – cutting speed.

Summing up the works of specific forces occurring on the elementary segment of cutting blade, we will get:
\[ P_z = \sum \Delta P_z \Delta \frac{K}{CC} \]
(6)
where \( K_{CC} \) – the factor of the chip complexity.

4. Determination of kinematic cutting parameters
Spatial mathematical model of the process of the blade machining is used for determining the kinematic changes of the cut angles and the geometry of the chip [8]. It includes a description of the motion of each elementary area of the cutting edge; moreover, the model allows to make the necessary calculations.

The process of machining is presented in the form of dependencies:
\[ X = f(\varphi(V), \varphi(S), \varphi(I), t, u); \]
\[ Y = f(\varphi(V), \varphi(S), \varphi(I), t, u); \]
\[ Z = f(\varphi(V), \varphi(S), \varphi(I), t, u); \]
(7)
where \( \varphi(V) \) – cutting speed parameter; \( \varphi(S) \) – carrying parameter; \( \varphi(I) \) – cutting blade parameter; \( t \) – time; \( u \) – control parameter.

The proposed mathematical spatial of cutting pattern mapping allows to calculate parameters of the machining process based on the use of vector analysis and numerical methods. The scheme presented in fig. 1.

The kinematic change of the back angle in the direction of the greatest movement of the flow is determined by the following formula:
\[ \Delta \alpha = \arctg \frac{\sqrt{X_F^2 + Y_F^2 + Z_F^2}}{\sqrt{X_V^2 + Y_V^2 + Z_V^2}}, \]
(8)
where \( X_F, Y_F, Z_F \) – the coordinates of the velocity vector in the direction of the handling; \( X_V, Y_V, Z_V \) – the coordinates of the vector of cutting movement.

The thickness of the cutting layer:
\[ a = \frac{X_aX_F + Y_aY_F + Z_aZ_F}{\sqrt{X_a^2 + Y_a^2 + Z_a^2}} \]
(9)
where \( X_a, Y_a, Z_a \) – are the coordinates of the vector in the direction of which the thickness of the shear layer changes.
The kinematic change of the front angle is determined by the following formula:

\[ \Delta \gamma = \arctg \left( \frac{a}{\sqrt{X_v^2 + Y_v^2 + Z_v^2}} \right) \] (10)

Then, it is necessary to compare the indicators of "energy efficiency of the cutting process" for different types of gears profile processing of spur bevel wheel (ms=6 mm, b=30 mm). We consider cutting in two passes, first (rough) is the method of cutting a trapezoidal cutter, the second (finishing) is performed by generating a standard finishing cutter shaping. Another option is cutting in one pass by the special stepped gear planing cutters, which is shown in fig. 2.

Table 1 – Comparison "energy efficiency of the cutting process" for different technological solutions for the machining of gear profiles of the spur bevel wheel

| Processing mode                      | In two cuts | In one strike by cutter with differentiated cutting scheme |
|--------------------------------------|-------------|----------------------------------------------------------|
|                                      | Roughing    | Finishing                                               |
| t_r, minute per tooth                | 0.56        | 0.15                                                    | 0.75 |
| U, meters per minute                 | 15          | 20                                                      | 13   |
| \( t_{mach} \), minute               | 22          |                                                          | 13.7 |
| \( K_1/K_{pro} \)                    | 1           |                                                          | 1.38 |
Line 4 of table 1 presents a comparison of energy criterion of cut. The value of K for processing into two passes was used as K₁. Analysis of the results of the analytical calculation shows that the standard processing option has a greater energy efficiency, however, is considered to be less effective in performance.

5. Conclusions
The achievement of environmental benefits is closely connected to the energy savings, as the use of any kind of energy resource is accompanied by emissions. The economic effect is achieved due to the reduction of the energy intensity of manufactured products, thereby the cost of production reduces.

The results showed that depending on the cutting conditions, the amount of energy spent on processing may considerably vary even when using the same processing method and tool. The use of the proposed methodology for assessing the efficiency of the cutting process at the stage of technological preparation allows to determine a rational processing method, the parameters of the technological system, processing modes and tool design, which are required for processing the detail with the necessary accuracy with minimal energy consumption.

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