The effect of machined wheel profile geometry on cutting force

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Abstract. The mechanisms based on standard geometry gears have reached their technological limits. To meet the needs of the market, it is necessary to meet new and new, often conflicting operational requirements. At the same time, it is necessary to reduce the mass of the node and increase the maximum torque, in addition, the noise level and increase the axial load must be reduced. To achieve the increasing requirements for the operational characteristics of mechanisms gears with specially designed tooth geometry are used. A tool for cutting such gears must be specially designed and manufactured for each new gear pair, given into account its design features. The introduction of a new tool in the technological processes of machining gear profiles leads to the fact that the surface quality decreases and tool wear increases. At present, the concept of this problem is scattered and composed of the experience of individual researchers. The work reveals the dependencies connecting physical phenomena accompanying the cutting process and the geometric parameters of the profile of the bevel gear. Based on the results of the project, it is possible to calculate the optimal profile parameters based on the technological parameters of the process.

1. Introduction
Mechanisms using transmission with gears of the standard geometry of the tooth profile have reached their technological limit. To achieve ever-increasing performance requirements, modern torque transmission mechanisms (gearboxes, reducing gears, differentials, etc.) use gears with specially designed tooth geometry. The main operational properties of a gear train are the perception of axial loads, the strength of the teeth, and the noise level. To control the strength of the teeth we change the angle of the tooth profile, increase the radius of rounding of the base of the tooth stem, and apply profile modifications. To reduce the noise level, we reduce the roughness and increase the contact area.

To achieve the ever-increasing performance requirements of torque transmission mechanisms in high-tech industries, gears with specially designed teeth geometry are used. The tool for cutting such gears must be specially designed and manufactured for each new gear pair, taking into account its design features. The introduction of a new tool in the proven technological processes of gear profile processing leads to a decrease in surface quality and increased tool wear. At present, the understanding of this problem is disjointed and consists of the experience of individual researchers [1, 2, 3].

To process the changed tooth profile, it is necessary to use a special cutting tool with a modified geometry of the cutting part. In practice, to use of a tool with a modified profile leads to a change in the predicted tool wear and machining accuracy. Currently, there are only scattered experimental data,
systematic data and recommendations are not available in the reference and scientific and technical literature. It can be suggested that these effects are observed due to the fact that the physical conditions of cutting change, the geometry of the cutting wedge bar, the chip removal mechanism, the friction forces on the front and back surfaces of the tool are being changed. The result is an increase in the cutting force and deterioration of the heatsink. Thus, having the ability to predict the physical phenomena accompanying the cutting process, it is possible to determine the rational geometric parameters of the cutting part, as well as adjust the cutting modes to achieve the required values of tool life and accuracy of the processed product.

In this paper, we consider the influence of the geometry of the teeth of a bevel gear on the cutting force that occurs during milling with a tool head. A significant influence of the profile geometry on the considered physical characteristic of the process means that the geometry of the tooth profile affects the practical results of processing. Therefore, when designing new gear profiles, it is necessary to take into account the technological conditions.

2. Modelling

The basis for models that predict the physical processes accompanying cutting is the methods of analytical, empirical, numerical and hybrid modelling [4]. Analytical modelling allows us to predict the cutting force, friction force, stress, strain, temperature, etc. However, due to the fact that cutting is accompanied by many complex physical phenomena, the use of analytical modelling in some cases is difficult. To predict the cutting force, analytical models based on the theory of sliding lines are used [4].

Empirical models are characterized by high accuracy and ease of use, but their development requires an array of experimental data, and the scope of application is limited. Designing a new empirical model requires a lot of time and material costs. Currently, the most widely used empirical approach is "Mechanistic Force Modeling". The essence of the method is to determine the specific forces per unit length of the cutting blade and then sum them over all the cutting edges involved in cutting. This method can be used to calculate the forces for cutting processes with a tool with a non-standard profile, when several edges are involved in the chip removal process. L. Berglind and D. Plakhonik developed a model for calculating the cutting forces that occur when processing parts of arbitrary configuration on five coordinate milling centres based on this approach [5].

The disadvantage of this approach is that if it is necessary to make any changes to the developed technological process (the use of new processing modes, the use of a new cutting tool, etc.), it is necessary to calibrate the model to clarify the correction coefficients. Calibration is carried out by conducting a set of experimental studies. After the model is calibrated, the forecast error will be less than 5% [6].

Since the late 70s, numerical methods have been used to simulate cutting. Numerical methods allow us to successfully model both small and large values of the cutting force, as well as solve problems in two-and three-dimensional space [1, 3, 7, 8]. Numerical models are easier and more convenient to study because of the ability to conduct computational experiments with them. The consistency and formality of numerical models allows us to identify the main factors that determine the properties of the object under study to research the response of the simulated physical system to changes in its parameters and initial conditions. The finite difference method and the finite element method have been used for the numerical solution of cutting thermal physics problems. Thanks to the development and increased availability of special software tools and computing power, it has only recently become possible to widely use numerical methods to solve cutting simulation problems.

K. D. Bouzakis [1] and others proposed a comprehensive method for modeling the process of gear milling with hobbing cutters. Calculations using the finite element method made it possible to predict temperatures, deformations, stresses, and a number of other physical variables that characterize the processes occurring in the cutting zone, and on their basis to predict the wear of the cutting tool.

F. Klocke [3] deal with the problem of the influence of the geometric parameters of the cutting tool, namely, the profile angle of the cutting bit and nose radius of the cutter tip on thermal and
mechanical stresses in the tool and the chip in the processing of bevel gears. The cutting process was modelled using the finite element method. In these works, particular solutions for the processes of processing gears of a certain profile are obtained, which allow us to establish some dependencies that arise during the processing.

Existing models for predicting the physical parameters of the cutting process are not adapted for studying the processes of gear processing of bevel gears due to the following features: the design of the tool, the cutting part of which is designed specifically for the processed pair of gears; the kinematics of the cutting process: continuous change in the geometric parameters of the cut metal layer and cutting angles; the chips formed by the top and side cutting edges, converging on the front surface of the cutter, chip fragments overlap each other, causing additional loads in the tool.

To solve the problem of predicting the cutting force that occurs during the mechanical processing of bevel gears, a method of predictive modelling has been developed [9]. Input data for modelling: the geometry of the cutting edge of the tool, processing modes, the behaviour of the material during deformation and the conditions of contact between the workpiece and the tool, the kinematics of the cutting process. Accepted assumptions: the tool is absolutely homogeneous and solid, the tool surface has a uniform structure, the processed material has a geometrically and physically nonlinear structure, the deformation of the workpiece is described by the Johnson-Cook method. The calculation scheme is shown in figure 1.

Figure 1. Calculation scheme for determining the parameters of the simulated process.

At the first stage, the parameters of the cut chip and the kinematic change in the geometry of the cutting part of the tool are calculated. To do this, an analytical method is used to calculate the parameters of the cut layer. At the second stage, three-dimensional modelling of the cutting tool and the workpiece is performed, considering the data obtained at the first stage. At the third stage, tests are conducted in a virtual environment. DEFORM 3D is used to simulate the processing.
The proposed approach allows us to calculate the axial components of the cutting force that occur during a single, most loaded cut. Next, we can change the system parameters under study and make repeated predictions to identify the influence of the parameters under study on the cutting force.

Verification of the adequacy of the simulation results was carried out by conducting experimental studies. Experimental work was carried out on the basis of a planning-machine (model GD320). For cutting, a special tool head was used, which allows modelling the cut under study within specified conditions [10]. To measure the axial components of the cutting force, a universal dynamometer UDM-600 was used. The dynamometer readings were recorded using a personal computer in the LabVIEW environment. The results of comparing the experimental and calculated values showed differences of no more than 12%. The proposed model can be considered adequate. Figure 2 shows a design scheme for a series of numerical experiments. Table 1 shows the initial data for carrying out numerical experiments.

![Design scheme](image)

**Figure 2.** Parameters of the simulated process.

| Cutting process parameter | Value    |
|----------------------------|----------|
| Chip thickness $b_1$, mm   | 0.04     |
| Chip thickness $b_2$, mm   | 0.06     |
| Cutting edge length $a_1$, mm | 2.9 |
| Cutting edge length $a_2$, mm | 0.4 |
| Kinematic change of edge $r$, mm | 0.01 |
| Rake angle $\alpha_s$, deg | 5        |
| Kinematic change of rake angle $\Delta \alpha_s$, deg | 0.025 |
| Clearance angle $\gamma_s$, deg | 5        |
| Kinematic change of Clearance angle $\Delta \gamma_s$, deg | 0.015 |
| Rake angle $\alpha_t$, deg  | 10       |
| Kinematic change of rake angle $\Delta \alpha_t$, deg | 0.02 |
| Clearance angle $\gamma_t$, deg | 6        |
| Kinematic change of Clearance angle $\Delta \gamma_t$, deg | 0.012 |
| Cutting speed $V$, m/min | 100      |
| Tool material              | WC       |
| Workpiece material         | 16MnCr5  |
3. Results
During the numerical experiment, options for changing the geometric parameters of the cutting part of the tool, depending on the geometry of the processed tooth profile, namely, the angle of the cutter profile and the radius of rounding of the cutter, were considered. The change in the angle of the cutter profile occurred in the range from 15 to 25 degrees. The change in the radius of rounding of the cutter occurred in the range from 0.1 to 0.2 mm. The selection of these ranges is based on practical recommendations. The values of the cutting forces are shown in the graphs, Figure 3. The purpose of this work was to establish the influence of the geometric parameters of the processed tooth on the cutting force, so figure 3 shows graphs of the change in the cutting force calculated as the root of the sum of the squares of the axial components of the cutting force. The expression for calculating the cutting force is represented by the dependence in equation 1.

![Figure 3. Graph of change in cutting force.](image)

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F = \frac{1047.5 - 7.4x + 2111.2y + 1065.9y^2}{1 + 6.5y - 17.3y^2}.
\]  

3.175.61
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2
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The relationship between the cutting force and the radius of rounding of the tip of the cutter can be explained by the fact that with increasing radius, the length of the cutting edge involved in cutting increases. Its significant influence can be attributed to the fact that the process of processing a tooth with a relatively small height (3 mm) was modeled, it can be assumed that with an increase in the height of the tooth, the influence of this parameter will decrease.

According to the study, when the profile angle decreases, the cutting force increases. This can be explained by the fact that when the angle decreases, the cutting conditions deteriorate, and chip removal is blocked.

Thus, the results of the simulation show that, depending on the change in the geometry of the processed wheel, the physical characteristics of the cutting process also change. In this case, changing the tooth geometry in the recommended range allows you to reduce the cutting force by more than 10% under the same processing conditions. Of course, in order to establish the exact qualitative and quantitative characteristics of the influence of tooth geometry on the cutting process, it is necessary to conduct a set of additional studies, but already at this stage it can be argued that taking into account the technological conditions when designing new gear profiles will increase the processing efficiency.
The proof that the profile geometry of the bevel wheel teeth has a significant impact on the practical results of processing means that it is possible to determine the rational profile parameters at which it is possible to simultaneously achieve: the required quality parameters of the product, the durability of the cutting tool and the reduction of the main time. This will improve the processing efficiency of bevel gears, as well as provide practical recommendations for optimizing the profile according to technological parameters.

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