Simulation of influence of cutting tool’s construction on specific heat energy in processing of bevel gears

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Abstract. To achieve the required performance characteristics of the bevel gear, optimization of the tooth cutting process is necessary. At the same time, in order to predict the wear of the tool, the quality and accuracy of the processed profile, it is important to understand the course of the thermal processes that occur during cutting. The paper presents the results of a study on modelling the effect of the design of a cutting tool on the thermal phenomena that arise during processing. The standard analysis of temperature fields does not allow determining the influence of rack and clearance cutting angles on thermal processes, other characteristics of the heat exchange process are considered in the work: heat flux and specific thermal energy. The basis for the work was the new mathematical model. The model developed by the authors represents a set of two different approaches to modelling: analytical and numerical. The developed model makes it possible to perform a numerical experiment with given conditions that are close to real practical ones.

1. Introduction
The treatment of bevel gears is one of the most important operations in the automotive industry, that requires optimization of the teeth’s geometry of the gears in order to achieve the required performance characteristics of the gear. The working part of the cutting tool for processing gears must be specially designed for each individual gear pair, taking into account the design features.

The understanding of influence of the working profile’s geometry of the tool on the thermal phenomena, which occur during the processing of bevel gears in the tool, workpiece and shavings is of critical importance for predicting tool wear, accuracy and surface roughness [1, 2]. Gearing efficiency affects all characteristics of the unit including vibratory [3].

Karpat Y., Özel T. [4] used a model that combines the theory of slip lines and analytical modeling for predicting temperature fields in the high-speed machining of AISI 4340 steel with a chamfer tool.

For the numerical solution of the problems of cutting thermal physics, the finite difference method (MCR) and the finite element method (FEM) have been applied. Lazoglu I., Altintas Y. [5] developed a finite difference method for predicting temperatures in tools and chips for the case of orthogonal cutting. Usui E. [6] calculated the temperatures in the cutting zone using FEM using the predicted cutting force. Some researchers used FEM to predict temperatures under different cutting conditions, tool materials, coatings, geometric parameters of the cutting edge [7, 8].
Simulation with the help of numerical methods allows to expand the range of problems solved by the model, and the calculation can be successfully performed for both small and large temperature values [9]. Numerical methods allow solving stationary and non-stationary problems in two- and three-dimensional space. It has become possible only recently to widely use numerical methods to solve the problem of modeling temperature fields, due to the development and increase in the level of availability of special software tools and computing power [10, 11].

2. Relevance
Improvement of technological processes (the introduction of new machines, new structural and tool materials) leads to an increase of temperatures in the processing zone [12]. Temperature becomes one of the factors limiting the productivity of operations and has a significant impact on product quality. That’s why there is a need to study the thermal phenomena, arising during the machining [13].

Classical research in the field of thermal physics of cutting is aimed at studying the most widespread and well-studied processes, such as turning and milling [7, 14] however, in the designs of modern machines and mechanisms, details with working surfaces, which require more complex machining, for example bevel gears wheels, are widely used.

The influence of the geometrical parameters of the cutting blade on thermal phenomena is given attention in the case when special tools are used or geometrically complex profiles, for example, gear wheels, are processed [15, 16]. For the processing of such surfaces, typically cutting with the removal of complex L- or U-shaped chips is used.

L- or U-shaped chips are formed by machining with a tool with a certain geometry of the cutting blade, when several adjacent cutting edges of one tool cut the chips simultaneously. Such chip formation is observed during the machining of gears, for example, during gear milling or cutting of a bevel gear [17, 18], and also in a number of cases when threading, pulling, etc.

Such tools have short time intervals between the overflows, and often reach the maximum permissible wear before the due time. The tool life limits the excessive wear of the cutting edges. Analysis of the wear of the gear cutting tool shows that the cause of the failure of the tool is chipping.

The disadvantage of this work is that the parameters studied by the authors - the pressure angle of the tool and tool corner radius - directly form the geometry of the working profile of the workpiece, in other words, the optimization of these parameters entails a change in the design of the gear.

3. Modelling the process of the bevel gear processing
Input data for modeling are: processing mode, tool cutting edge geometry (pressure angle of the cutter, tool corner radius, rack and clearance cutting angles), material behavior during deformation and contact conditions between the workpiece and the tool.

The parameters of the cut-off chips and the geometry of the cutting part of the tool are determined using an analytical model of universal technique for calculating the parameters of the shear layer proposed by A.S. Tarapanov and G.A. Kharlamov [19] taking into account their kinematic variation.

The following assumptions: the workpiece is stationary; all the movements, necessary for shaping, are made by the tool; the tool is absolutely homogeneous and absolutely solid; the surface of the tool has a uniform structure; the processed material has a geometrically and physically nonlinear structure; deformation of the billet is described by the Johnson-Cook method using the Mises’ plasticity criterion; rolling takes place along the pitch circle of the wheel without sliding.

3.1. Analytical modelling
In general, the mathematical representation of the cutting scheme for an arbitrary selected tool in Cartesian coordinates can be represented as follows [19]:
where \( X, Y, Z \) – coordinates of the cutting edge point of the tool; \( S \) – Feed parameter; \( V \) – cutting speed parameter; \( \Delta h \) – geometry parameter of the cutting edge.

The obtained spatial mapping of the cutting scheme allows to calculate the position of each individual point of the cutting edge in space at any time and, accordingly, in the subsequent stage of simulation, it will be possible to determine the kinematic variation of the tool working angles and the thickness of the cut layer.

3.2. Numerical modelling

For the numerical simulation of the processing, the Deform3D program was used. The program allows to implement a finite element analysis of the cutting processes and uses for this purpose the implicit Lagrange method with continuously changing grid.

In the postprocessor of the program, the finite element simulation is simulated by generating a mesh for the tool and the workpiece. In order to increase the accuracy of calculations in areas where the workpiece is subjected to an increased local load, a smaller grid that is continuously changing during the simulation is used. Simulation of processing by means of a "shallow" mesh is used only in deformation zones and for chips. The effect of the machining process on the condition of the workpiece is not the subject of this project, so a large mesh is used for the rest of the workpiece.

The decisive value on the quality of the results is provided by a correct description of the behavior of the material during plastic deformation and the correct determination of friction between the chips and the front surface of the tool.

As the model of the cutting tool is an object that is an element of an instrument having a geometry similar to the geometry of the cutting blades of the tool. For the sake of simplicity, the model lacks structural elements that do not affect the cutting process. The workpiece model is an element of a bevel gear, which is the machined lateral side of the tooth and tooth cavity. Models are created in the Kompas environment, and saved using the *.STL data format.

4. Investigation of thermal processes occurring during the processing of a bevel gear

Figure 1 shows the scheme used to simulate the processing of bevel gears. The geometry of the chips was obtained by means of analytical modeling of the cutting process, the cutting conditions are typical for machining a bevel gear in the middle of a cut.

![Figure 1. Calculation scheme for numerical simulation.](image)

The basic data for the examined simulation case are presented in table 1.
### Table 1. Initial data for numerical simulation

| Cutting process parameter                                      | Value | Cutting process parameter                                      | Value |
|---------------------------------------------------------------|-------|---------------------------------------------------------------|-------|
| Chip thickness removable with side cutting edge \( b_1 \), mm  | 0.2   | Tip cutting angle of the side cutting edge \( \gamma_b \), grad | 6     |
| Chip thickness removable with vertex cutting edge \( b_2 \), mm | 0.07  | Kinematic change in the tip angle of the lateral cutting edge \( \Delta\gamma_b \), grad | 0.015 |
| Length of side cutting edge \( a_1 \), mm                    | 2.9   | Clearance angle of cutting of the vertex cutting edge \( \alpha_v \), grad | 8     |
| Length of vertex cutting edge \( a_2 \), mm                  | 0.4   | Kinematic change of the clearance angle of the vertex cutting edge \( \Delta\alpha_v \), grad | 0.02  |
| Pressure angle of the tool \( \alpha \), grad                 | 20    | Tip cutting angle of apical cutting edge \( \gamma_b \), grad | 6     |
| Tool corner radius \( r_0 \), mm                             | 0.2   | Kinematic change of the front corner of the vertex cutting edge \( \Delta\gamma_b \), grad | 0.012 |
| Curvative radius of cutting edges \( r \), mm                | 0.01  | Cutting speed \( V \), m/min;                                | 100   |
| Clearance angle cutting edge \( \alpha_v \), grad             | 5     | Tool material                                                 | WC    |
| Kinematic variation of the clearance angle of the lateral cutting edge \( \Delta\alpha_v \), grad | 0.025 | Workpiece material                                            | 16MnCr5 |

4.1. Influence of geometrical parameters of the cutting part of the tool on the thermal phenomena arising during processing

In the process of carrying out a numerical experiment, options for changing the geometric parameters of the cutting part of the tool, namely the front and rear angles of the cutting, were considered. The change in the tip angle occurred in the range from 6 to 12 degrees. The change in the clearance angle occurred in the range from 5 to 15 degrees.

The graph of the change in the value of the heat flux as a function of \( \gamma \) and \( \alpha \) is shown in figure 2.

![Figure 2](image1.png)

**Figure 2.** Graph of heat flux in the tool, depending on the angle of inclination of the cutting edges.

![Figure 3](image2.png)

**Figure 3.** Graph of change in specific heat energy depending on rack and clearance cutting angles.

The results of the numerical experiment show that as the anterior and posterior angles increase, the values of the heat flux decrease. In this case, the tip angle has a greater influence, so when the angle is
increased from 6 to 12 degrees, the heat flux decreases by 10%, and with an increase in the clearance angle from 5 to 15 degrees, the heat flux decreases by 6%. This can be attributed to the fact that as the angles γ and α increase, the cutting forces Px, Py, Pz decrease to a certain extent, and the intensity of heat generation sources in the cutting zone decreases accordingly.

However, the front and rear corners of the tool affect the ability of the tool to draw heat from the cutting area. When the angles are increased together or separately, the tool sharpening angle decreases, so the heat sink is braked into the cutter body. For a tool that removes complex chips, this becomes critical, since the heat sink is complicated by the maximum heated portion – tool corner radius. In order to assess the effect of the anterior and posterior corners of the instrument on the heat sink process, a specific heat energy index was used. Specific heat energy shows how much energy is needed to heat 1 mm$^3$ by 1°C.

Since on the time interval under study (from 0 to 3 ms) the tool is heated, the specific heat energy was calculated from the experimental data at a certain time $t = 2.5$ ms.

The formula for calculating the specific heat energy:

$$q = \frac{Q}{\sum_{i} V_{i}} \cdot V_{i} t \geq 20^\circ C$$

where $Q$ – the heat flux at the time being investigated, W; $i$ – number of instrument volumes with the same temperature; $V$ – the volume of the instrument in which the temperature is assumed constant, mm$^3$; $t$ – the temperature, °C.

The graph of the change in the specific heat energy as a function of γ and α is shown in figure 3.

The graph of the change in the specific heat energy increases in the range of variation of the tip angle from 6 to 9 degrees and decreases from 9 to 12, while the change is significant and is about 40%. An increase in the value of the clearance angle is reflected in the graph by a decrease in the value of the specific heat energy, for the range of variation of the clearance angle, the range of variation of the specific heat energy is 15%.

5. Conclusion
A three-dimensional model of the process of formation of temperature fields in the tool, the processed billet and shavings, arising during the processing of the tooth profile of the conical wheel with a tool head, is developed. The model is based on the methodology of the spatial mapping of the cutting scheme, supplemented by studies of thermal physics of the cutting process, performed using finite element analysis methods.

The simulation results show that the geometric parameters of the cutting tool affect the thermal processes occurring in the tool. The heat flux decreases with an increase in the rack and clearance cutting angles. The specific heat energy increases in the range of the tip angle variation from 6 to 9 degrees and decreases from 9 to 12. The increase in the value of the clearance angle is reflected in the graph by the decrease in the specific heat energy value for the considered range of the change in the clearance angle. The tip angle has a greater influence on the thermal processes than the rear.

The tip angle γ and the clearance angle α have a different effect on heat generation and heat removal, which leads to the fact that for specific cases of the design of the cutting tool (the profile being processed) it is possible to set the angular values corresponding to the rational (optimum) temperature.

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