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DEFINITION OF THE GEOMETRIC PARAMETERS OF THE UNDEFORMED CHIP AT THE CUT-IN STAGE WHEN MACHINING AN EXTERNAL GEAR USING THE POWER SKIVING METHOD

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Abstract. In this study, the process of tool plunging into the workpiece during external tooth cutting will be modelled. Cut-in is one of the most dangerous stages not only in gear turning, but also in any cutting process. The gear cutting process is analytically studied in terms of maximum chip thickness and, on this basis, recommendations for process design are offered. The developed simulation is able to calculate the appropriate cutting geometry for each revolution of the tool cut-in to the workpiece. Using the designed cutter profile and transition surface, the depth of penetration of the tool into the workpiece can be calculated for discrete time and space intervals. Finally, the developed simulation was tested on a gear with an external gear crown.

This article describes the kinematics of gear cutting at the plunging stage and the algorithm for its modelling. In the description of the gear cutting kinematics, a method for creating a gear cutting simulation model was presented. In addition, an analytical method for calculating the maximum chip thickness was applied and confirmed by simulation.

Key words: external gears; power skiving process; undeformed chip; simulation; maximum chip thickness; cut-in.

Introduction

In recent years, the use of Power Skiving has become increasingly common in the production of gears. Today, it is used in the world's leading gear manufacturing facilities. Its popularity is primarily due to its high productivity, flexibility, precision and versatility. It is also known as gear skiving in the scientific literature and in gear manufacturing. It is increasingly being used to cut both external and internal gears, including spur and helical gears. In some cases it is also used to cut bevel gears [1]. The technical capabilities of CNC machines and significant advances in the manufacture of specialised gear cutting tools have allowed the application of this method to expand. Today, it is replacing more familiar methods such as gear milling, gear shaping and broaching. Thanks to high cutting speeds and effective synchronisation of workpiece and cutter movements, the power skiving method enables gear teeth to be cut quickly and precisely to an accuracy level of 7 degrees and a high quality tooth surface to be produced in a short time [2].

These are defining characteristics for the application of gear skiving in any competitive company engaged in mainstream production and mass production [3]. Currently, Japan, Germany and China are the world leaders in the application and research of gear skiving. Given the relatively recent introduction of this method of gear cutting, it is still in the process of refinement and development. This is evidenced by numerous studies conducted by the world's leading research institutes and laboratories. The main challenge is to select the optimum technological parameters for cutting high quality gears with external or internal crowns.

Fig. 1. Illustrates the process of cutting an external gear in the factory [2]

The selection of a suitable cutting tool with rational geometric parameters – a cutter – is also an important part of the technological process. The stationary process of the cutter and the quality of the obtained tooth surface depend on the correctly selected tool, its design, the shape of the inserts and their arrangement. The purpose of this study is to model the process of tool engagement in the workpiece during the cutting of external teeth. This critical stage of the cutting process is one of the most dangerous not only in gear skiving but in any cutting operation. It is well known that tool breakage most often occurs during engagement [4]. During the cutting process, the stages of engagement and withdrawal of the tool from the material are accompanied by dynamic processes of vibration, impact and abrupt alternating stresses.

Review of primary sources

The power skiving process is increasingly the subject of active research in many countries around the world. At present, researchers are mainly focused on improving the cutting tool or determining the optimum cutting technological parameters on the respective equipment. Most of the work on power skiving is based on modelling the process and then comparing the results with numerical experiments. The results of such studies partially confirm theoretically calculated values with practically obtained data. Almost all authors use powerful software that introduce certain simplifications in the reproduction of the cutting process. In particular, the authors [1] attempted to describe the kinematics of cutting teeth on a gear and to reproduce the modelling algorithm. Using SPARTAPRO Berg and other software, they created models of the workpiece and the tool. They obtained chip cross-sections for the passes, constructed two different profiles of the gears and presented an analytical method for calculating the maximum chip thickness. However, the reproduction of the cutting process was shown with some displacement, and the cutter profile was modelled asymmetrically, leading to some distortion in the results.

Basic research was carried out by Eiri NAGATA and others [3] when the method was applied to the mass production of gears. The results of the research were obtained through numerical experiments on CNC machines, and the authors achieved some success in reducing vibrations and selecting technological parameters. However, it was not possible to claim definitive analytical solutions for the selection of feed or cutting thickness. The company BAUER [5] developed a model for process design with a multi-pass cutting strategy. Chip welding was identified, which could be a consequence of negative rake angles in the process, but the authors did not determine cutting forces or models for deformed chips.

Moriwaki investigated the time-dependent changes in rake angle and cutting depth. He concluded that the transverse axis angle has a significant influence and that at the end of the cutting motion, maximum cutting depth and negative rake angles prevail [6].

The research in [7] focuses on modelling the kinematics of the cutting process using commercial CAD software, and the author provides undeformed chips and calculated cutting forces. However, the author considers a straight lateral profile of the cutter and incorrectly reproduces the kinematics of the process, leading to inadequate results.

Analysing the research results and considering the rapid development of this relatively new method of gear cutting, it can be concluded that there are still many unresolved issues during machining. These are primarily related to the complex kinematics of the process and the associated challenges in reproducing the cut. In most of the research presented, modelling and computational software has been used to support the research activities. One of the modelling possibilities is the finite element method [8].

Research Results

While finite element modelling provides results close to those obtained from experiments, it requires high computational power and expertise for model tuning. More computationally efficient are results obtained from analytical calculations. It is necessary to analytically describe the motion of two bodies (workpiece-cutter), i.e. to determine their positions at each instant of time. By superimposing the respective profiles of the gear and the cutter relative to each other, the cross-section of the chip formed can be obtained for the position considered. The calculation of the geometric cut of the tool into the workpiece is a set of two-dimensional superimpositions of linear planes of their profiles. The results of gear cutting modelling using this method have been successfully confirmed in the past [9]. Evaluation of the modelling results allows the cutting process to be understood. It is also possible to generate a digital design of the final geometry of the gear [10] and the chip [11].

To perform the cutting calculation, it is necessary to describe the tool and the workpiece in parametric form. We will use the method already described [12] for the power skiving process, but during cutting. While a stable cutting regime has been considered for different cutting technological parameters [12], the cutting stage is crucial and extremely important in the discussed gear skiving method. It can influence the determination of the number of passes and change the recommended technological values.

The gear turning process is analysed from the point of view of maximum chip thickness and recommendations for process design are proposed. The simulation developed is capable of calculating the corresponding cutting geometry for each revolution of the tool engaging the workpiece. Chip thickness, chip area and the results obtained are calculated and recorded in a table. Using the designed cutter profile and transition surface, the penetration depth of the tool into the workpiece can be calculated for discrete time and space intervals. Finally, the developed simulation was tested on a gear with an external crown gear.

Example

Let’s consider the case of cutting a spur gear with the following parameters:
Involute spur gear.
Module 2.5 mm.
Number of teeth: gear 33, cutter 24.
Axial feed 0.75 mm/rev.
Cutting speed 190 m/min.
Four passes.
Cutter material – hard titanium-tantalum alloy.
Angle of rake and intersection of cutter teeth 25 degrees.
Crown height 22 mm.
Coefficient of friction on the face for the given speed 0.63.
Total depth evenly distributed over the passes: 1.25 mm each.

In order to obtain a correct chip cut and a realistic reproduction of the gear cutting process, it is necessary to calculate analytically the position of the cutter blade and the resulting recess in the gear obtained on the previous revolution. Such calculations were carried out using the system of equations of intersection of an oval (cutter) and a circle (gear), formulated for the practical example mentioned and confirmed by 3D modelling (Fig. 2).

This ensured computer-aided design (CAD) environments, solid models involved in the process reproduce the cutting process with the best accuracy available. For each of these positions, the exact position of the cutter and the intermediate position of the workpiece at that moment have been determined. Simulations also allow the cutting process to be visualised and improve the understanding of the turning process.

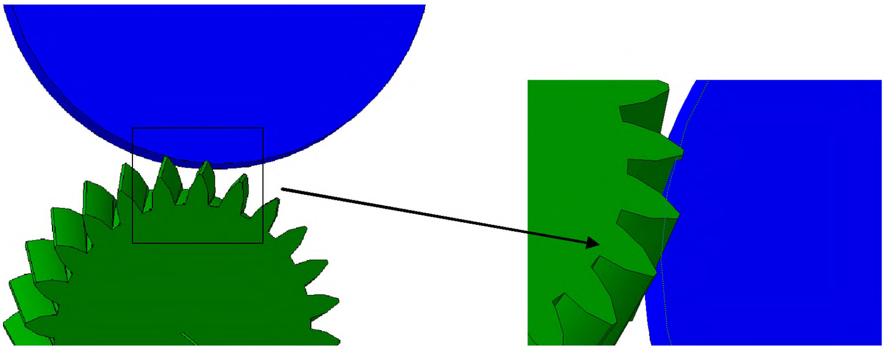


Fig. 2. 3D modelling of the Power Skiving process

In order to accurately represent Power Skiving, a simulation model was created to reflect the movements of the tool:

n_{cut} – the frequency of rotation of the tool around its axis;

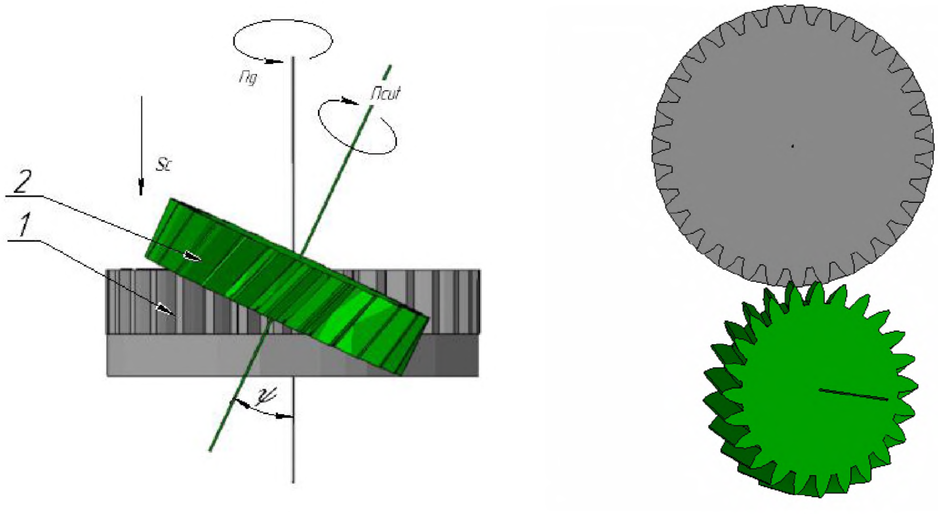
n_g – the frequency of rotation of the gear workpiece about its axis;

Ψ – the angle of inclination of the tool relative to the workpiece. In our case its value is 25^0.

S_c – tool feed along the axis of rotation of the gear part.

The approach used in the model, where sequential profiles are used to describe the movement of the tool in three-dimensional space, provides better control over the accuracy of the solid created.

To model the cutting process, all the movements involved in the process are considered at a particular point in time and fixed at a particular position. Tool 1 rotates around its own axis at a given speed V_{cut}. The axis is inclined by a certain angle Ψ (Fig. 3) and it also moves along the axis of rotation of the workpiece – V_{feed}.



a *b*

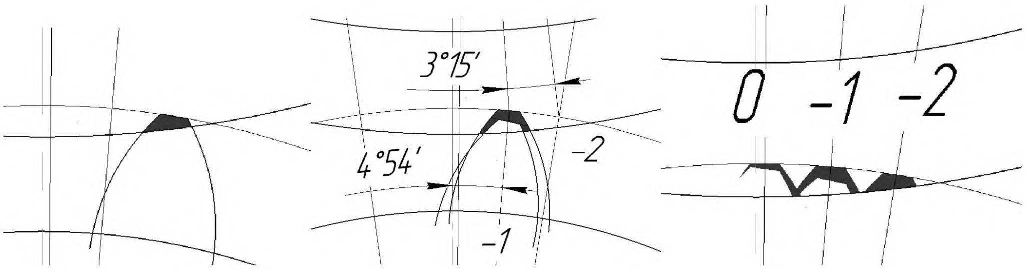
Fig. 3. Power skiving tool and workpiece arrangement: a – front view; b – top view

Fig. 3 shows the 3D model of the tool and workpiece arrangement for the power skiving process. The simulation model reflects each discrete position of the cutter and gear, and by superimposing the transitional cut surface obtained at the *i*-th revolution and the cutter position on the *i*+1 position, the profile of the cut can be obtained. The first step in modelling is to create and position the transition surface profile. For ease of visualisation, let's project it onto a plane.

Considering that the axial distance between the gear and the cutter will vary for each pass, we will distribute the area of tool engagement with the gear workpiece according to the pass. On the first pass, when the depth of overlap is 1.25 mm (Fig. 4, *a*), we will divide the area of tool engagement with the gear workpiece into 3 successive angular positions, marked –2, –1, 0. The first rotation of the cutter, during which the cutting takes place, will correspond to position –2 (position shifted to the right of the vertical at 9.3^0), on the second rotation – position –1 (4.9^0) and on the third rotation – position 0 angle equal to 0.6^0 (angles determined by analytical calculations). In this case, the angular step between positions is 4.34°. For the next pass, with an overlap depth of 2.5 mm, there will already be 4 such positions, as the overlap zone will be larger in this case (Fig. 4, *b*). For this depth, we will designate a new position –3, as it will correspond to the cut on the first pass. In this way, we calculate all the basic positions of the cutter for each pass and for each depth.

a *b*

Fig. 4. Projections of the cutter blade onto the workpiece during cutting for different turns:
a – for the first pass (depth 1.25 mm); b – for the second pass (depth 2.5 mm)



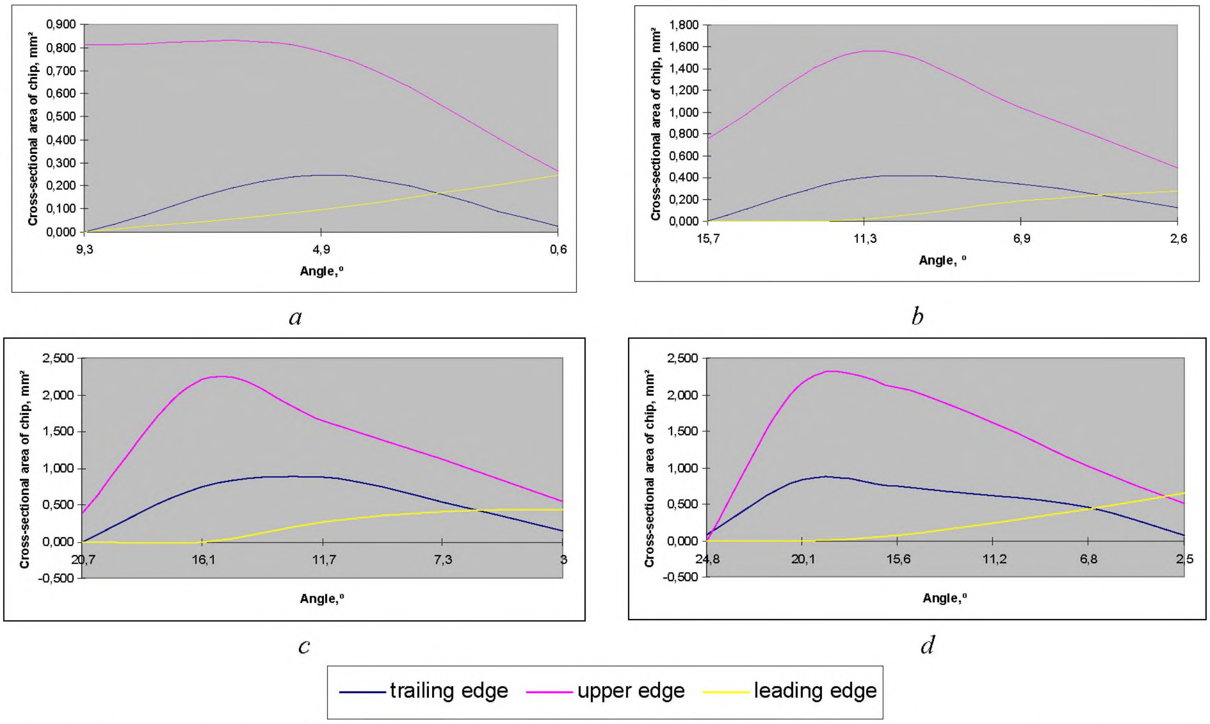
a *b* *c*

Fig. 5. Positioning the cutter blade from entry to exit

As the workpiece is still intact during the first pass and the first turn of the cutter blade, the first cut is solid and corresponds to the overlap of the cutter blade and the workpiece (Fig. 5, *a*). On the second pass, the cutter blade profile will be at position –1 and the cut obtained after the first pass must be set at a position offset by the feed multiplied by the gear ratio. It is necessary to align the cutter blade profile and the cut obtained after the first pass – we will obtain the second cut (shaded area) (Fig. 5, *b*). We do the same for the next position. We obtain a series of cuts on each revolution (Fig. 5, *c*). At this depth of overlap, the tool/workpiece process will reach a steady state by the fourth revolution. In this article, we won't be interested in this, as it has already been discussed in other works [12]. We will carry out the same procedure for the next overlap depths – 2.5 mm, 3.75 mm and 5 mm. As can be seen from Fig. 4, in order to achieve a stable cutting mode with a greater overlap depth, the number of cutting revolutions increases and, accordingly, the number of positions. In particular, at a full cutting depth of 5 mm, six cuts into the workpiece are required to achieve a steady state of tool operation.

Research results

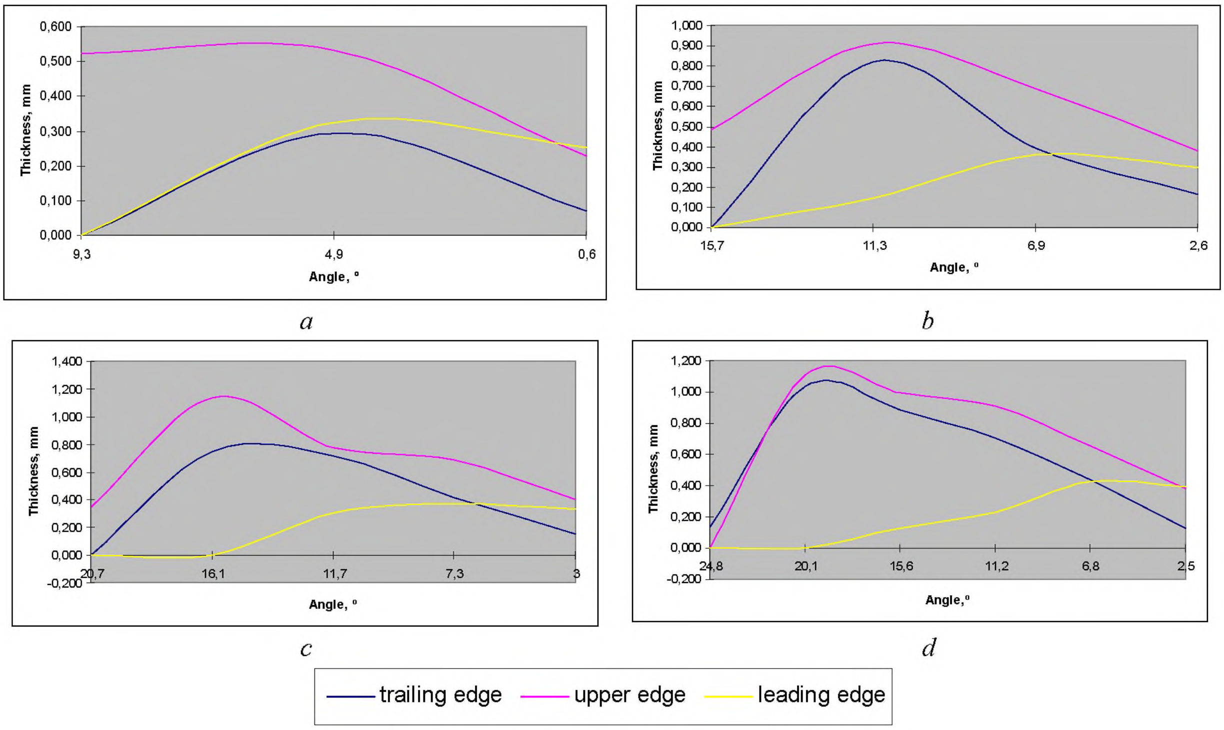
Modelling was carried out for the cutting of an external gear (input data see above) and the results are shown graphically (Fig. 6, 7).



a *b*

c *d*

Fig. 6. Illustrates the dependence of the change in the cross-section of the undeformed chip and its variation with the position of the cutter blade: a – at a cutting depth of 1.25 mm; b – at a cutting depth of 2.5 mm; c – at a cutting depth of 3.75 mm; d – at a cutting depth of 5 mm



a *b*

c *d*

Fig. 7. Depicts the relationship between the change in the thickness of the undeformed chip and its dependence on the position of the cutter blade; a – at a cutting depth of 1.25 mm; b – at a cutting depth of 2.5 mm; c – at a cutting depth of 3.75 mm; d – at a cutting depth of 5 mm

To better understand the operation of the cutter blade, let's divide its blades into parts: entry, tip and exit. Analysing the cut from each part of the tool will allow us to adequately see the work of each part and draw conclusions to further improve the tool. The influence of the perception of the type of change in chip thickness and its area according to the position of the cutter blade is shown in these results (Fig. 6).

Such investigations can also be carried out for different axial tool feeds, at different tilt angles, for cutting gears with different modules and tooth numbers.

Conclusions

As can be seen in the figure, the cutting edge of the cutter has the highest values, both in terms of area and thickness. It therefore places the greatest load on the cutting table. In all cases, the cutting process starts from the leading edge (except for the first cut at a depth of 1.25 mm). In the next rotation, the cutter works with all the knives. From the plot (areas) it can be seen that the area of the undeformed chip gradually increases for the exit and top blades, but decreases after the third rotation of the cutter. The nature of the change in the area of the chip cross section for the exit and top knives is similar, but the top knife is loaded 3–4 times more than the exit knife (depending on the cutting depth). The work of the entry blade, on the other hand, increases gradually with each successive revolution of the tool and reaches its maximum value in the last revolutions of the cut, but the cuts on this blade are the smallest at the beginning of the cut and correspondingly increase to their maximum values in the final positions.

As expected, the chip area and chip thickness values increase significantly with each subsequent pass, and at such depths and feeds, the tool and equipment are subjected to significant loads and temperatures that adversely affect the tool's performance. It is obvious that such regimes are unsuitable for cutting. Even under steady-state cutting conditions with a feed of 0.5 mm/rev for 4 passes, it is possible to achieve cutting [2]. However, for cutting regimes, these working conditions are extremely detrimental.

In the case under consideration, it can be seen that the swarf area only on the upper blade exceeds 2 mm^2 and the total swarf area is more than 3 mm^2, which is absolutely unacceptable for the operation of the tool. In this case, it is essential to reduce the depth of cut (increase the number of passes and reduce the feed rate). Depending on the characteristics of the equipment and its performance parameters, it is possible to select the optimum technological values and to determine the final cutting indicators.

This article describes the kinematics of gear cutting and the simulation algorithm. The description of the gear cutting kinematics includes methods for creating a simulation model and the coordinate systems required to transform the tool profile coordinate system to the workpiece profile coordinate system and vice versa. Based on the algorithm, profiles of undeformed chip cuts were constructed for external spur gears.

In addition, an analytical method for calculating the maximum chip thickness was applied and confirmed by simulation. A comparison between the analytically calculated maximum chip thickness and the simulated maximum chip thickness shows good agreement in the results. The obtained chip thickness and chip cut areas can be used as indicators to control and optimise the cutting process. With full information on the geometric dimensions of the undeformed chip, surface roughness and qualitative characteristics of the process can also be determined.

In gear cutting, there are various strategies and approaches for controlling the cutting process. Possible options include adjusting the feed rate according to the selected number of passes, ensuring that it remains within the force and power limits of the machine. The number of passes can be varied for a given axial feed and, in any case, it is necessary to consider the cutting speed that will allow an acceptable tooth surface quality and precision to be achieved. As can be seen from the initial data, the given task requires multifactorial research to find the optimum choice of technological parameters, the main objective of which is the machining time.

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