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MODELING OF UNDEFORMED CHIP IN POWER SKIVING GEAR CUTTING PROCESS

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Summary. *The method of cutting gear wheel by the Power skiving method is considered and the principle of creating non-deformed chip when cutting external spur gear is analyzed in detail in this paper. The task of this investigation is to develop an adequate model of chip formation and to analyze quantitative estimates of parameters of slices in Power skiving process. In order to solve this problem, complex system of grapho-analytical, mathematical and computer modeling of this process is developed. It takes into account its kinematics and reliably reproduces the regularities of cutting-forming processes. The grapho-analytical method developed by I. E. Hrytsai for worm tooth milling is used to model the parameters of the sections. The continuous movement of cutting and forming is presented in the form of successive discrete movements of the contour of the tooth, and its linear and angular positions relative to the processed gear wheel are easily described mathematically. This greatly simplifies the model and geometric constructions using existing CAD systems, unlike other known methods. In each position of the tooth, its contour in the front surface is combined with the contours of the teeth, which performed cutting in the previous positions both along the axial feed and on the helical line. The main condition for the accurate determination of the parameters of the cuts is the establishment of the shape and dimensions of the surface, which is formed in the process of steady cutting in each cavity of the gear wheel between the treated surfaces of the teeth and the raw surface of the workpiece for 1 revolution of the cutter. To investigate the parameters of the slices, the schematic arrangement of the gear wheel and the cutter is depicted and the process is divided into discrete states. The results of modeling according to the above mentioned parameters are given in the form of graphic dependencies: chip cross-sectional area, thickness depending on different axial feeds of the cutter and for different modules of the gear wheel. The dependence of the change in the geometric characteristics of the undeformed chip on the position of the cutter is obtained. In further research, it is possible to establish a number of other physical quantities and their interdependence during gear cutting using the Power skiving method.*

Key words: *undeformed chip, Power skiving, graphoanalytical method, sliding fracture, chip cross-sectional area, cutter, legal path.*

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Statement of the problem. Technological innovations in the production of gears, such as Power skiving, brought a new stage in the development of their manufacturing technology. Due to the increase in productivity and efficiency, this method of cutting the toothed crown has gained wide application in recent years, mainly due to the possibility of continuous chip removal. Despite the fact that Power skiving was first described back in 1910 [1], but due to the increased requirements for the rigidity of the machines, the need for high degree of synchronization of the rotational movements of the workpiece and the cutting tool at very high angular speeds, the process was not used for a long time. In addition, there were no suitable tools available at the time that were able to withstand the elevated temperatures that occur during the cutting process, all of which precluded the use of this method. Only now, with the development of machine tools and the acquisition of suitable tool, Power skiving is increasingly used in modern enterprises.

Today, Power skiving is one of the most effective technologies for cutting spur or helical gears with external or internal ring gear, which allows you to get the shape of the teeth with

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high speed and accuracy. When cutting gears, you can get 7–8 degrees of accuracy of the toothed crown, which is absolutely sufficient for wide use in various mechanisms, nodes, and machines. Experimental studies have shown that the process of cutting gears using the Power skiving method is many times faster than conventional methods of their production. This technology combines elements of turning and milling, ensuring very short production time and thus has extremely high performance. In particular, cutting the gear wheel 70 mm wide with module of 5 mm and which has 26 teeth takes 214 seconds.[2]! Given the importance of this problem for the theory and practice of dental processing, many scientific schools in Europe, Japan, and Asia worked on its solution.

Relevance of the topic. In this paper, the method of cutting the gear wheel by the Power skiving method is considered and the principle of creating non-deformed chip when cutting the external spur gear is analyzed in detail. Obtaining the parameters of the cross-section of the chips, which is formed during the operation of the cutter, can be attributed to the most important characteristics of the Power skiving process. Complete information about the dimensions (width, length, thickness of the chip, its area) and the shape of the cut layers, their size in different sections (input, output and upper part) of the tooth at each moment of cutting time, as well as establishing the regularity of their continuous cyclical change during the rotation of the cutting tool, serve as the basis for comprehensive reproduction and description of various interconnected and interdependent deformation and contact processes that occur during the cutting process of the toothed crown. This makes it possible to analyze thermal and force phenomena, to establish the amount of friction and wear of the tool. Such processes can be investigated both in static mode and in dynamic one.

Thus, a number of physical quantities depend on the parameters of the sections:

1. the average value of the cutting force and its fluctuations per revolution of the cutter;
2. friction forces on the front, upper and back surfaces of the blades;
3. kinematic angles that change during the passage of the tool's trajectory during cutting;
4. the necessary work required to remove the allowance and overcome the friction on the surfaces of the cutter teeth;
5. heat flows into the body of the tool and the intensity of its heating;
6. wear of cutter teeth and their resistance to operation;
7. transient dynamic processes that determine the regularities of force formation and cutting temperature on tooth surfaces.

Therefore, detailed investigation of the parameters of the cross-section of the slices at each moment of time, which can be obtained after cutting the chips with the cutter, can serve as the basis for comprehensive study of the tooth turning process by the Power skiving method.

The task of this research is the development of adequate models of chip formation, quantitative assessment of parameters of slices in the Power skiving process, which is relevant at the moment. To solve such problem, it is necessary to develop complex system of grapho-analytical, mathematical and computer modeling of this process, which takes into account its kinematics and reliably reproduces the regularities of the cutting-forming processes. In this system, the results of each previous stage form the basis for the next modeling step in the following sequence: 3D model of the undeformed chip ® determination of parameters of cut layers ® calculation of deformation and contact intensity parameters ® modeling of cutting and friction forces ® modeling of heat flows and temperature ® calculation of machining errors and prediction of wear ® selection of rational cutting modes and structural and geometric parameters of the disc cutter and coating.

Analysis of available literature recourses. In the last decade, considerable amount of experimental research and modeling of the Power skiving tooth cutting process has been carried out. With this method of slicing, the authors of the work [3] note the wear of the cutting tool. The relevant work was focused on determining the undeformed geometry and chip thickness [4, 5], as well as calculation of cutting force components [6]. Chip deformation mechanisms were also analyzed using FEM-enabled simulations, where temperatures, strains and stresses in the cutting tool could also be predicted [7].

Author [8] developed the algorithm capable of calculating the undeformed chip geometry, represented as a series of two-dimensional chip sections along the axis of the workpiece. The simulation model was based on the same methodology that was developed in papers [9, 10] and allowed the calculation of cutting forces using the Kienzle-Victor force model. In paper [11] the simulation model that was able to predict the optimal parameters of the gear cutting process was developed. The authors of paper [12] developed geometric model that made it possible to predict the deviation of the tooth profile. In paper [13] the authors focused on improving the SPART Apro software they had already created for the manufacturing process of tooth turning. This software product allows you to simulate the Power skiving process.

In paper [14] the power parameters of the cutting process were investigated. Papers [15, 16] are devoted to the investigation of the design of tools and their geometric parameters influence on power indicators during the processing of gear wheels.

The relationship between tool geometry and technological parameters and cutting conditions is studied in paper [17]. The effect of coatings and changes in the geometric parameters of the cutting tool on the cutting process are analyzed in paper [18].

In paper [19], the influence of process parameters on chip thickness and sliding speed is analyzed, tool wear is analyzed, and the occurrence of chip welding to tool surfaces during the cutting process is investigated.

Paper [20] provides the approach to computer simulation of the process of chip formation and calculation of its thickness, as well as the morphology of wheels cut by the Power skiving method.

However, in the above mentioned papers [3–7], the authors do not take into account the shape and dimensions of the transition surface, which is formed in the intermediate depression between the teeth and the tool in the previous axial position of the tool during the feed movement. It is the shape of this surface that determines the inner surface of the removed chip, its shape and dimensions.

In papers [8–13], the results of geometric modeling and quantitative parameters of the chip, in particular, the thickness of sections, their area are not properly used as the basis for further and deeper research of this process. After all, the majority of various force, contact, tribological and thermal phenomena depend on their values and laws of change in the movement of the tool.

A significant drawback of papers [14–20] is the inaccurate reproduction of the kinematics of the process. The cutting movement is formed by the combination of two movements – the axial feed and the speed of the main movement, which is given to the tool, and not to the workpiece, as is customary in the specified papers. As the result, the resulting velocity vector will be directed at different angle relative to the base surfaces and axes. This is important for the correct determination of cutting forces, friction and geometrical parameters of the tool.

Kinematic scheme of the Power Skiving process. Power skiving is continuous machining process where there is constant contact between the tool and the gear being produced. The process reproduces the engagement of the gear wheel and pinion in the gear train (Fig. 1) [21]. The difference is that the cutting tool, in addition to rotary motion with frequency n_t, still moves along the axis of rotation of the workpiece V_f and located at angle w to the axis of rotation of the gear wheel (Fig. 2).

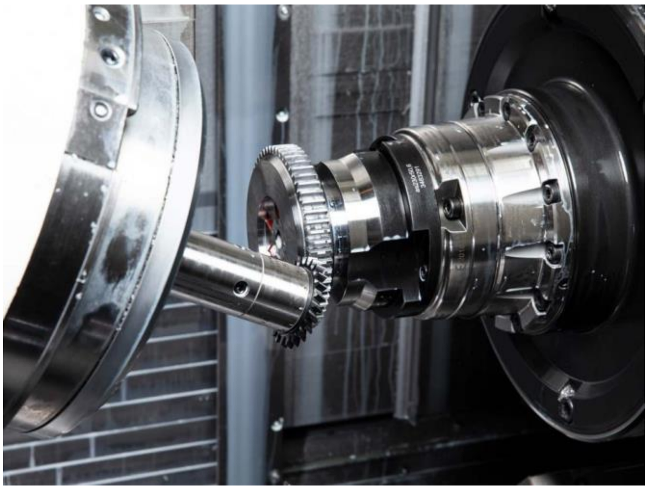
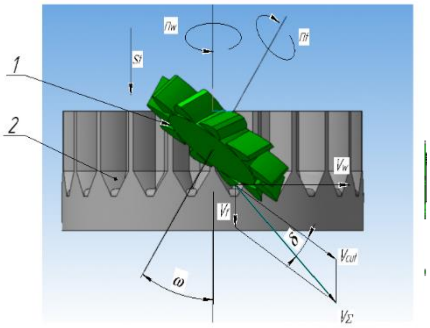


Figure 1. Overview of the external ring gear cutting process on machining center for the Power skiving process

Cutting speed V_{cut} is created by the inclined angle w between the axis of the gear being produced and the axis of the tool (Fig. 2). This figure shows the tool pos. 1 (green), which is located at angle to the crown; both rotate at high speed with proportional frequencies n_t and n_w.



1 – cutter; 2 – gear blank

Figure 2. Kinematic diagram of the Power skiving

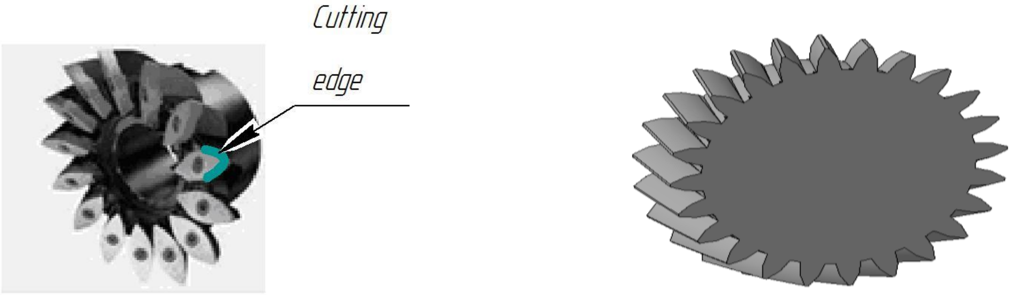
At the scheme (Fig. 2) it is marked: V_w – linear velocity of rotational movement of the part at the considered point; V_{cut} – the linear velocity of the cup cutter at the point under consideration; V_f – the linear speed of the tool movement along the axis of the workpiece, which coincides with the speed of tooth reduction along the feed axis due to the intersection of the axes; V_Σ – the speed of the total resulting cutting motion.

According to this approach, the main movement, that is, the cutting movement, is the rotation of the cutter, which is combined with the movement of the cutter along the axis of the workpiece (for spur gear), resulting from the intersection of the axes. Then the resulting cutting motion that describes vector V_Σ will be the geometric sum of these two movements. This allows you to display the kinematics of the process and present the graphic image dependences of the parameters of the cut on the length of the cutter in usual, orthogonal coordinates and directions of the axes.

Cutting speed V_{cut} – is the relative velocity between the front surface of the cutting tool and the surface of the recess in the workpiece being machined. It is proportional to the angle of inclination ω between the axis of the tool and the axis of the workpiece (Fig. 2).

Larger bevel angle results in higher cutting speed for the same peripheral speed V_w. That is, we can achieve the required cutting speed by reducing the number of revolutions by increasing the angle of inclination – larger angle is more advantageous. But in practice, there are a number of restrictions on the angle of inclination (machine capabilities, mutual location of the workpiece and the tool), therefore, as a rule, such angle will be taken as 20 degrees, which is compromise when cutting by the Power skiving method.

The main cutting edge of the cup cutter is sharpened, it precisely cuts the contour of the gear wheel during engagement (Fig. 3).



a) general view b) 3D model

Figure 3. Typical assembled cutter with mechanical clamping for the Power skiving method

Basics of modeling undeformed chips. We will consider all processes of tooth cutting in the fixed cut – after cutting, but before the cutter exits, when processing spur gears with external crown. The regularities of the tooth turning process, cross-sections, and features of the formation of the profiles of the sections revealed for these conditions can be completely used for slightly modified conditions: – during cutting in and out of the threading tool and approximated (with appropriate changes) to the processing of helical gears or the processing of gear wheels with inner crown.

The grapho-analytical method developed by I. E. Hrytsai for worm gear milling was used to model the parameters of the sections, the essence of which was as follows [22]. In cutting and forming methods with complex kinematics, which also includes Power skiving, four relative movements of the tool and the workpiece take place. Such movements in tooth milling with the worm cutter are the rotary movement of the cutter (main movement), the rotary movement of the circular feed provided to the wheel workpiece, the axial movement of the tool along the axis of the workpiece, as well as the constructive movement of the point belonging to the helical surface of the worm cutter in the axial direction for the cutter, tangential to the dividing surface of the gear wheel. Similar kinematics takes place in the Power skiving method, but the constructive movement of the point on the working surface of the cup cutter occurs due to the intersection of the axes of the cutter and the gear wheel. The trajectory of the described movements is described by splines, which are formed in the form of imaginary traces of the movement of the tooth of worm cutter.

As well as the constructive movement of the point belonging to the helical surface of the worm cutter in the axial direction for the cutter, tangential to the dividing surface of the gear wheel. Similar kinematics takes place in the Power skiving method, but the constructive movement of the point on the working surface of the cup cutter occurs due to the intersection of the axes of the cutter and the gear wheel. The trajectory of the described movements is described by splines, which are formed in the form of imaginary traces of the movement of the tooth of the worm cutter. CAD systems, unlike other known methods. In each position of the tooth, its contour in the front surface is combined with the contours of the teeth, which performed cutting in the previous positions both along the axial feed and on the helical line. The superimposition of these contours and their intersection forms the instantaneous section of the chip in the given specific position, which is repeated for each subsequent discrete position in accordance with the kinematics of the tooth cutting process. On the basis of these consecutive instantaneous sections, it is possible to monitor the operation of individual blades, the dynamics of chip formation, and reproduce its actual shape and dimensions.

Based on this approach Fig. 4 shows the reduction of tooth contours to the axis of symmetry of this tooth.

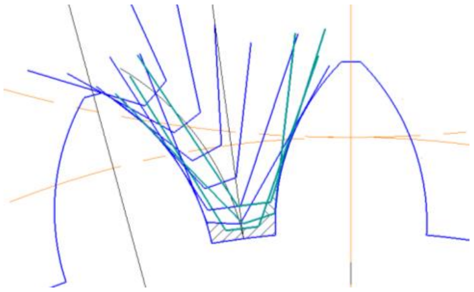


Figure 4. The array of tooth contours and construction of the cross-section of the cutting surface formed by this set during tooth milling with he worm cutter

We will analyze the tooth turning process using the Power skiving method, as one of the most productive methods at the moment.

Construction of instantaneous cross-sections of slices. The main condition for the accurate determination of the parameters of the cuts is to establish the shape and dimensions of the surface, which is formed in the process of steady cutting in each cavity of the gear wheel between the treated surfaces of the teeth and the raw surface of the workpiece for 1 revolution of the cutter. Instantly machined surface is formed by the active tooth during «engagement» with the workpiece. There can be from 2 to 5 of them in operation at any moment – it depends on the parameters of the gear wheel that is being cut and on the parameters of the tool (module, number of teeth). When this intermediate surface is next processed (after 1 revolution), the tool will move down by the amount of feed along the axis of rotation of the gear wheel, and thus cut the next layer of chips. The cutting process takes place due to the difference in the sliding speed of the profiles due to the intersection of the axes of the wheel and the tool at a certain angle, which, when cutting spur gears, is equal to the angle of elevation of the helical line of the cutter. Within this transition surface, each subsequent cutting cycle in the same cavity continues after the rotation of the workpiece and movement of the cutter by the value of the axial feed. This transition surface of the cavity determines the actual shape and dimensions of the instantaneous section of the cut, which vary uncertainly with the angle of rotation of the tooth, and are periodically repeated in the machining cycle.

During the axial movement of the cutting tool, each of its teeth moves along the same trajectory, occupying the same circumferential position relative to the elementary surface of the cut profile. In other words, due to the rigid kinematic connection between the working movements of cutting and forming in the tooth turning process, during each cut, the tooth blade is in contact with the formed profile once during the period of one revolution of the gear wheel, and the cutting surface of the blade remains unchanged for the given initial conditions. The periodic contact of each cup cutter (its blade) with the workpiece is combined with the continuity of cutting and forming in the process of rolling due to the constructive movement of the cutter, movements of rolling and axial feed.

The chip that is cut by separate tooth of the tool in the process of fixed cutting, that is, in the intermediate position of the workpiece and the cutter at a certain distance from the end of the wheel. The cutting area of the tooth will be determined by the angle φ turning and projecting into the end plane of the cutter. begins to form on the angle φ_{in}, and completes its formation at the angle of rotation of the cutter φ_{out}, 0 position – corresponds to the perpendicular position of the tooth. moving during the given turn along the axis of the wheel in the feed motion (Fig. 5). Thus, the trajectory of the tooth movement is circular, and not rectilinear, as presented by most authors who studied Power skiving.

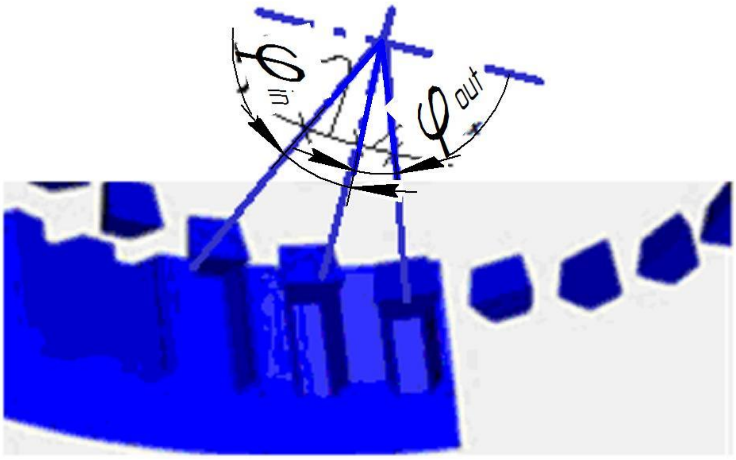


Figure 5. Motion path of the cutter's teeth in the Power skiving process

To study the parameters of the slices, let's depict the schematic arrangement of the gear wheel and the cutter and divide the process into discrete states (Fig. 6). These conditions determine the position of the teeth of the cutter relative to the interaxial perpendicular. t.B1 is the point that lies on the top of the tooth that cuts into the workpiece and it is located at the intersection of circles with radii R_{a2} and R_{a1}.

R_{a2} – the radius of the circle to the tip of the cutter;

R_{a1} – the radius of the circle to the top of the gear;

In the plane of the end of the workpiece, with zero rotation of the tooth relative to this plane, this tooth is at the distance x from the interaxial perpendicular O_1O_2.

From triangles O_1B_1O and B_1OO_2 we will find the distance *x,* which is equal to half the chord *C.* For this, we will make the following notations:

C – the length of the chord, which is equal to the distance between the point of insertion of the cutter and the point of exit from the cutting zone $C = 2x$;

j_{in} – the central angle between the radius drawn to the cut-in point and the vertical axis of symmetry (the interaxial perpendicular of the MOP). We can divide this angle into 5 equal segments before the interaxial perpendicular and 5 after it passage. In this way, we will create 10 discrete positions of the cutter tooth through the corner $j = j_{in}/5$.

A – wheelbase;

We will find the coordinate of the tip of the tool tooth in each position. For this, it is necessary to set the value *x* and *y*.

$$A = \frac{m \cdot (z_1 + z_2)}{2}$$

$$x^2 = R_{a1}^2 - y^2 = R_{a2}^2 - (A - y)^2$$

$$y^2 - (A - y)^2 + R_{a2}^2 - R_{a1}^2 = 0$$

$$y^2 - \left(A^2 - 2Ay + y^2\right) + \left(R_{a2}^2 - R_{a1}^2\right) = 0$$

$$2Ay - A^2 + \left(R_{a2}^2 - R_{a1}^2\right) = 0$$

$$y = \frac{A^2 + R_{a1}^2 - R_{a2}^2}{2A}$$

$$x = \sqrt{R_{a1}^2 - y^2}$$

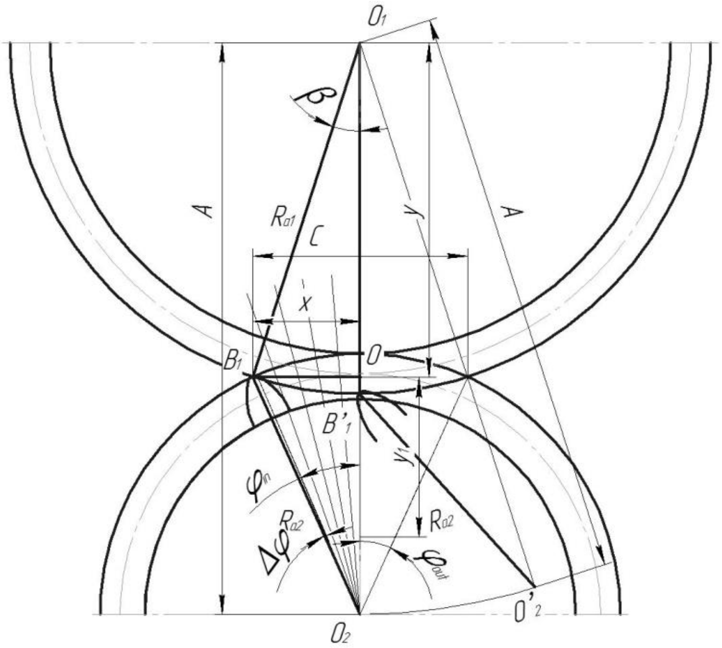


Figure 6. Scheme for geometric calculation coordinates for the top cutter of the tooth

In order to reproduce the transition surface, which is the principle position of this work, it is necessary to turn the profile of the cutter tooth relative to the center of the axis of rotation of the gear wheel O_1 to the interaxial perpendicular. In this way, we will get a new placement p.B_1 – p.B'_1. In order to obtain the first *i*- position of the tool blade, we will rotate the triangle $O_1B_1O_2$ relative to p.O_1 on the angle b and we will get its new position $O_1B'_1O'_2$. And at the next rotation of the gear wheel, the cutter blade will accept a new one *i+1*-the position shifted to angle Dj.

After that, we perform the same action for the displaced tooth of the tool. We will get shifted contour of the blade, and the difference of these contours will show us the first shape of the cross section of the undeformed chip. We will carry out such procedures with all discrete states of the cutter blade, as the result of which we will obtain a set of cuts for the entire chip – from the beginning of the cutting of the tool to its exit from the cutting zone (Fig. 7).

Simulation results. To study the parameters of the cuts that are formed from two directions – the axial feed and the rotation of the cutter, we will separate the consecutive positions. Let's break down the trajectory of the cutter into 10 positions:

- position -5, -4, -3, -2, -1 will correspond to angle φ_{in}, where -5 is the cutting position of the cutter tooth blade in the workpiece. The following positions will correspond to its gradual approach to perpendicular placement – 0 (Fig. 7 a);
- position 0 – the tooth of the cutter is located perpendicular to the wheel and corresponds to the middle of the entire trajectory;

- position -1, -2, -3, -4, -5 will correspond to angle φ_{out}, where -5 is the position of the blade of the cutter tooth exiting the workpiece. After passing through the middle location (position 0), the tooth will gradually disengage from position -1 to -5 (Fig. 7 a).

The next cut in this depression will occur through complete revolution of the gear wheel. During this time, the cutter will move in axial direction by the value of axial feed. Let's carry out the same procedure for dividing the trajectory of the «cutting path» of the cutter (Fig. 6 b).

a b

Figure 7. Complex of contours cutter of the tooth during cutting in and out at the i-th revolution (a) and i+1 revolution (b)

If we superimpose these two projections on each other, we will get sections of the chip in each position (Fig. 8).

As the research object, we will choose the cutter, 3-D model of which will look like in Fig. 5. with the following characteristics: m=5mm, z=24, which cuts the gear wheel z=33.

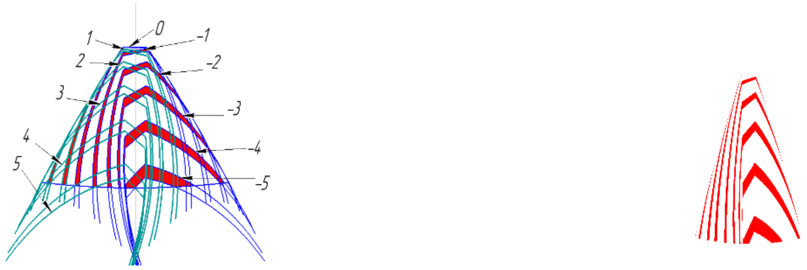


Figure 8. The array of chip sections obtained during each position of the cutter

The results of modeling according to the above mentioned parameters are given in the form of graphic dependencies: chip cross-sectional area (a) and thickness (b) depending on different axial feeds of the cutter and for different modules of the gear wheel (Fig. 9–10);

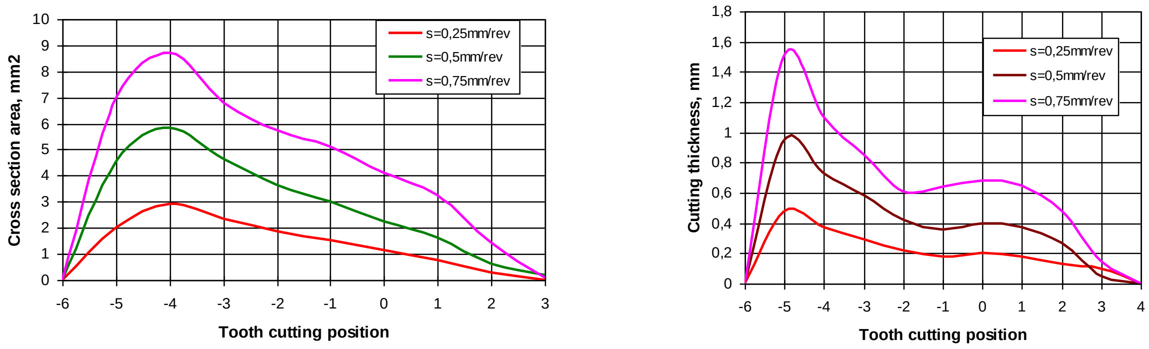
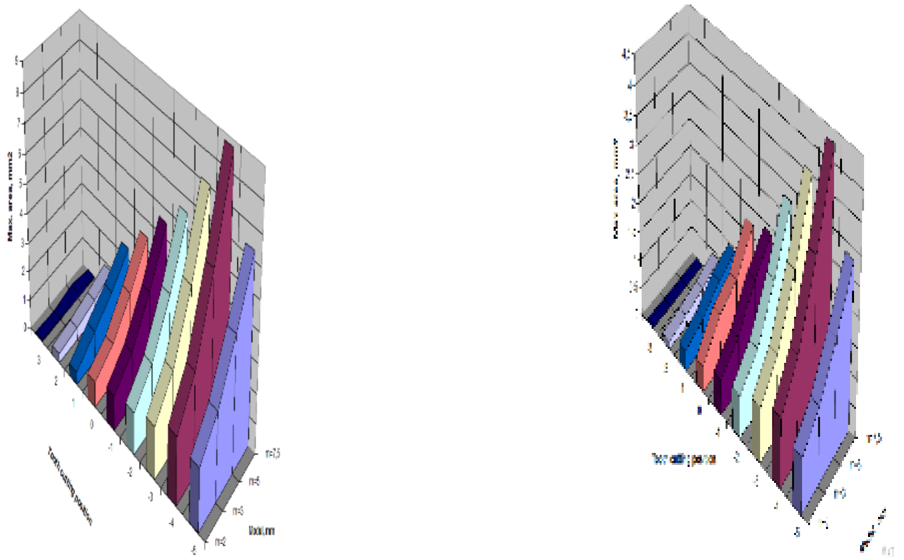


Figure 9. Parameters of the cross-section of the sliding fractures by the angle of rotation of the cutter for 5mm module



a) for feeding 0.5 mm/rev

b) for feeding 0.25 mm/rev

Figure 10. Dependence of the area of the perpendicular section's chip on the module and the position of the cutter

Conclusions. If you analyze the graphic dependencies (Fig. 9–10), you can establish the following characteristic features:

a) the thickness of the slices is almost directly proportional to the axial feed of the tool. This trend persists for different gear cutting modules. Thus, by changing the axial feed of the cutter, we can choose more acceptable feed to avoid zones of «rubbing» – lack of cutting. Such cases are possible under the condition that the thickness of the section is less than the radius of the cutting edge of the blade.

b) the maximum slice thickness always falls on the initial position, for different feeds and modules (Fig. 9 b). Further, the thickness of the chip gradually decreases, although it should be noted that in the position of the cutter close to MOP (position -2...1 in Fig. 9) it is almost unchanged;

c) the influence of the axial feed on the thickness of the slice is almost directly proportional. But the module, as it turned out, does not change the maximum thickness of the slice. The fluctuation of this value does not exceed 10% for different modules, which turned out to be unexpected.

d) analyzing the dependence of maximum slice thickness on the position of the cutter, it can be divided into 3 zones: 1 – a zone of large thicknesses that gradually decrease (positions -5.. -2) 2 – stable zone. Here, the thickness almost does not change (position – 2..1); 3 – zone of small thickness (position 1..3). In this zone, the thickness is not significant and it also gradually decreases. As a rule, after the 3rd position of the cutter tooth, cutting does not occur.

e) if we analyze the areas of sections for different feeds and modules (Fig. 10), it should be noted that the growth of these values leads to larger areas, which should have been expected. 2-fold increase in the axial feed of the results in similar increase in the cross-sectional area. But maximum value of the area does not fall on the -5 position, like the maximum thickness, but on -4. In this way, it increases from the moment the tool is inserted to the -4 position, and then gradually decreases.

So, having obtained the dependence of the change in the geometric characteristics (thickness, length, area, shape) of the undeformed chip on the position of the cutter, in further investigations we can establish a number of other physical quantities (cutting forces, thermal characteristics, oscillations) and their interdependence during gear cutting using the Power skiving.

References

1. Ren Z., Fang Z., Arakane T., Kizaki T., Nishikawa T., Feng Y., & Sugita N. Parametric modeling of uncut chip geometry for predicting crater wear in gear skiving. Journal of Materials Processing Technology. 2021. Vol. 290. 116973. https://doi.org/10.1016/j.jmatprotec.2020.116973
2. URL: https://www.youtube.com/watch?v=ks3Fb2qiqJg&ab_channel=SecoTools.
3. Ren Z., Fang Z., Kobayashi G., Kizaki T., Sugita N., Nishikawa T., & Nabata E. Influence of tool eccentricity on surface roughness in gear skiving. Precision Engineering. 2020. Vol. 6. P. 170–176. https://doi.org/10.1016/j.precisioneng.2020.02.007
4. Vargas B., Zapf M., Klose J., Zanger F., & Schulze V. Numerical modelling of cutting forces in gear skiving. Procedia CIRP. 2019. Vol. 82. P. 455–460. https://doi.org/10.1016/j.procir.2019.04.039
5. Onozuka H., Tayama F., Huang Y., & Inui M. Cutting force model for power skiving of internal gear ournal of Manufacturing Processes. 2020. Vol. 56. P. 1277–1285. https://doi.org/10.1016/j.jmapro.2020.04.022
6. Inui M., Huang Y., Onozuka H., & Umezu N. Geometric simulation of power skiving of internal gear using solid model with triple-dexel representation. Procedia Manufacturing. 2020. Vol. 48. P. 520–527. https://doi.org/10.1016/j.promfg.2020.05.078
7. McCloskey P., Katz A., Berglind L., Erkorkmaz K., Ozturk E., & Ismail F. Chip geometry and cutting forces in gear power skiving. CIRP Annals. 2019. Vol. 68. No. 1. P. 109–112. https://doi.org/10.1016/j.cirp.2019.04.085
8. Bergs T., Georgoussis A., & Löpenhaus C. Development of a numerical simulation method for gear skiving. Procedia CIRP. 2020. Vol. 88. P. 352–357. https://doi.org/10.1016/j.procir.2020.05.061
9. Klocke F., Brecher C., Löpenhaus C., Ganser P., Staudt J., & Krömer M. Technological and simulative analysis of power skiving. Procedia Cirp. 2016. Vol. 50. P. 773–778. https://doi.org/10.1016/j.procir.2016.05.052
10. Spath D., & Hühsam A. Skiving for high-performance machining of periodic structures. CIRP Annals. 2002. Vol. 51. No. 1. P. 91–94. https://doi.org/10.1016/S0007-8506(07)61473-5
11. Bouzakis K. D., Friderikos O., & Tsiafis I. Fem-supported simulation of chip formation and flow in gear hobbing of helical gears. Proceedings of DET2007 4th International Conference on Digital Enterprise Technology Bath, United Kingdom 19–21 September 2007. P. 34–43. https://doi.org/10.1016/j.cirpj.2008.06.004
12. Brecher C., Brumm M., & Krömer M. Design of gear hobbing processes using simulations and empirical data. Procedia CIRP. 2015. Vol. 33. P. 484–489. https://doi.org/10.1016/j.procir.2015.06.059
13. Bouzakis K. D., Lili E., Michailidis N., & Friderikos O. Manufacturing of cylindrical gears by generating cutting processes: A critical synthesis of analysis methods. CIRP annals. 2008. Vol. 57 (2). P. 676–696. https://doi.org/10.1016/j.cirp.2008.09.001
14. Guo E., Hong R., Huang X., & Fang C. Research on the cutting mechanism of cylindrical gear power skiving. The International Journal of Advanced Manufacturing Technology. 2015. Vol. 79 (1). P. 541–550. https://doi.org/10.1007/s00170-015-6816-9
15. Guo E., Hong R., Huang X., & Fang C. A novel power skiving method using the common shaper cutter. The International Journal of Advanced Manufacturing Technology. 2016. Vol. 83 (1). P. 157–165. https://doi.org/10.1007/s00170-015-7559-3
16. Guo E., Hong R., Huang X., & Fang C. Research on the design of skiving tool for machining involute gears. Journal of Mechanical Science and Technology. 2014. Vol. 28 (12). P. 5107–5115. https://doi.org/10.1007/s12206-014-1133-z
17. Hühsam A. Modellbildung und experimentelle Untersuchung des Wälzschälprozesses. Inst. für Werkzeugmaschinen und Betriebstechnik. Universität Karlsruhe. 2002.
18. Bechle A. Beitrag zur prozesssicheren Bearbeitung beim Hochleistungsfertigungsverfahren Wälzschälen. Shaker. Aachen. 2006.
19. Klocke F., Brecher C., Löpenhaus C., Ganser P., Staudt J., & Krömer M. Technological and simulative analysis of power skiving. Procedia Cirp. 2016. Vol. 50. P. 773–778. https://doi.org/10.1016/j.procir.2016.05.052
20. Tapoglou N. Calculation of non-deformed chip and gear geometry in power skiving using a CAD-based simulation. The International Journal of Advanced Manufacturing Technology. 2019. Vol. 100 (5). P. 1779–1785. URL: orcid.org/0000-0001-9126-5407. https://doi.org/10.1007/s00170-018-2790-3
21. URL: https://mav.industrie.de/werkzeuge/horn-waelzschaelen-von-verzahnungen-power-skiving/#slider-intro-2.

22. Hrytsay I. YE. Teoretyko-prykladni osnovy kompleksnykh naukovykh doslidzhenʹ protsesu narizannya zubchastykh kolis. Lʹviv: Spolom, 2009. 254 p. [In Ukrainian].

Список використаних джерел

1. Ren Z., Fang Z., Arakane T., Kizaki T., Nishikawa T., Feng Y., & Sugita N. Parametric modeling of uncut chip geometry for predicting crater wear in gear skiving. Journal of Materials Processing Technology. 2021. Vol. 290. 116973. https://doi.org/10.1016/j.jmatprotec.2020.116973
2. URL: https://www.youtube.com/watch?v=ks3Fb2qiqJg&ab_channel=SecoTools.
3. Ren Z., Fang Z., Kobayashi G., Kizaki T., Sugita N., Nishikawa T., & Nabata E. Influence of tool eccentricity on surface roughness in gear skiving. Precision Engineering. 2020. Vol. 6. P. 170–176. https://doi.org/10.1016/j.precisioneng.2020.02.007
4. Vargas B., Zapf M., Klose J., Zanger F., & Schulze V. Numerical modelling of cutting forces in gear skiving. Procedia CIRP. 2019. Vol. 82. P. 455–460. https://doi.org/10.1016/j.procir.2019.04.039
5. Onozuka H., Tayama F., Huang Y., & Inui M. Cutting force model for power skiving of internal gear ournal of Manufacturing Processes. 2020. Vol. 56. P. 1277–1285. https://doi.org/10.1016/j.jmapro.2020.04.022
6. Inui M., Huang Y., Onozuka H., & Umezu N. Geometric simulation of power skiving of internal gear using solid model with triple-dexel representation. Procedia Manufacturing. 2020. Vol. 48. P. 520–527. https://doi.org/10.1016/j.promfg.2020.05.078
7. McCloskey P., Katz A., Berglind L., Erkorkmaz K., Ozturk E., & Ismail F. Chip geometry and cutting forces in gear power skiving. CIRP Annals. 2019. Vol. 68. No. 1. P. 109–112. https://doi.org/10.1016/j.cirp.2019.04.085
8. Bergs T., Georgoussis A., & Löpenhaus C. Development of a numerical simulation method for gear skiving. Procedia CIRP. 2020. Vol. 88. P. 352–357. https://doi.org/10.1016/j.procir.2020.05.061
9. Klocke F., Brecher C., Löpenhaus C., Ganser P., Staudt J., & Krömer M. Technological and simulative analysis of power skiving. Procedia Cirp. 2016. Vol. 50. P. 773–778. https://doi.org/10.1016/j.procir.2016.05.052
10. Spath D., & Hühsam A. Skiving for high-performance machining of periodic structures. CIRP Annals. 2002. Vol. 51. No. 1. P. 91–94. https://doi.org/10.1016/S0007-8506(07)61473-5
11. Bouzakis K. D., Friderikos O., & Tsiafis I. Fem-supported simulation of chip formation and flow in gear hobbing of helical gears. Proceedings of DET2007 4th International Conference on Digital Enterprise Technology Bath, United Kingdom 19–21 September 2007. P. 34–43. https://doi.org/10.1016/j.cirpj.2008.06.004
12. Brecher C., Brumm M., & Krömer M. Design of gear hobbing processes using simulations and empirical data. Procedia CIRP. 2015. Vol. 33. P. 484–489. https://doi.org/10.1016/j.procir.2015.06.059
13. Bouzakis K. D., Lili E., Michailidis N., & Friderikos O. Manufacturing of cylindrical gears by generating cutting processes: A critical synthesis of analysis methods. CIRP annals. 2008. Vol. 57 (2). P. 676–696. https://doi.org/10.1016/j.cirp.2008.09.001
14. Guo E., Hong R., Huang X., & Fang C. Research on the cutting mechanism of cylindrical gear power skiving. The International Journal of Advanced Manufacturing Technology. 2015. Vol. 79 (1). P. 541–550. https://doi.org/10.1007/s00170-015-6816-9
15. Guo E., Hong R., Huang X., & Fang C. A novel power skiving method using the common shaper cutter. The International Journal of Advanced Manufacturing Technology. 2016. Vol. 83 (1). P. 157–165. https://doi.org/10.1007/s00170-015-7559-3
16. Guo E., Hong R., Huang X., & Fang C. Research on the design of skiving tool for machining involute gears. Journal of Mechanical Science and Technology. 2014. Vol. 28 (12). P. 5107–5115. https://doi.org/10.1007/s12206-014-1133-z
17. Hühsam A. Modellbildung und experimentelle Untersuchung des Wälzschälprozesses. Inst. für Werkzeugmaschinen und Betriebstechnik. Universität Karlsruhe. 2002.
18. Bechle A. Beitrag zur prozesssicheren Bearbeitung beim Hochleistungsfertigungsverfahren Wälzschälen. Shaker. Aachen. 2006.
19. Klocke F., Brecher C., Löpenhaus C., Ganser P., Staudt J., & Krömer M. Technological and simulative analysis of power skiving. Procedia Cirp. 2016. Vol. 50. P. 773–778. https://doi.org/10.1016/j.procir.2016.05.052
20. Tapoglou N. Calculation of non-deformed chip and gear geometry in power skiving using a CAD-based simulation. The International Journal of Advanced Manufacturing Technology. 2019. Vol. 100 (5). P. 1779–1785. URL: orcid.org/0000-0001-9126-5407. https://doi.org/10.1007/s00170-018-2790-3
21. URL: https://mav.industrie.de/werkzeuge/horn-waelzschaelen-von-verzahnungen-power-skiving/#slider-intro-2.
22. Грицай І. Є. Теоретико-прикладні основи комплексних наукових досліджень процесу нарізання зубчастих коліс. Львів: Сполом, 2009. 254 с.

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МОДЕЛЮВАННЯ НЕДЕФОРМОВАНОЇ СТРУЖКИ ПРИ НАРІЗУВАННІ ЗУБЧАСТОГО КОЛЕСА МЕТОДОМ POWER SKIVING

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Резюме. *Розглянуто метод нарізування зубчастого колеса методом Power skiving та детально проаналізовано принцип побудови недеформованої стружки при нарізуванні зовнішнього прямозубого вінця. Завдання дослідження – розроблення адекватної моделі стружкоутворення та проаналізовано кількісні оцінки параметрів зрізів у процесі Power skiving. Для вирішення такого завдання розроблено комплексну систему графоаналітичного, математичного і комп'ютерного моделювання цього процесу, де враховано його кінематику й достовірно відтворено закономірності процесів різання-формоутворення. Для моделювання параметрів зрізів використано графоаналітичний метод, розроблений І. Є. Грицаєм для черв'ячного зубофрезерування. Неперервний рух різання і формоутворення представлено у вигляді послідовних дискретних переміщень контура зубця, а його лінійні й кутові положення відносно оброблюваного зубчастого колеса легко піддаються математичному описанню. Це значно спрощує модель і геометричні побудови з використанням існуючих CAD систем на відміну від інших відомих методів. У кожному положенні зубця його контур у передній поверхні суміщається з контурами зубців, які виконували різання в попередніх положеннях як по осьовій подачі, так і на гвинтовій лінії. Головною умовою точного визначення параметрів зрізів є встановлення форми та розмірів поверхні, яка утворюється в процесі усталеного різання в кожній западині зубчастого колеса між обробленими зубцями поверхнями та необробленою поверхнею заготовки на 1 оберт різака. Для дослідження параметрів зрізів зображено схематичне розташування зубчастого колеса і різака та розділено процес на дискретні стани. Результати моделювання за вказаними вище параметрами наведено у вигляді графічних залежностей: площа перерізу стружки, товщини залежно від різних осьових подач різака і для різних модулів зубчастого колеса. Отримано залежності зміни геометричних характеристик недеформованої стружки від положення різака. У подальших дослідженнях можна встановити цілий ряд інших фізичних величин та їх взаємозалежність під час нарізування зубчастого колеса методом Power skiving.*

Ключові слова: *недеформована стружка, Power skiving, графоаналітичний метод, зріз, площа перерізу стружки, різак, дискретне переміщення.*

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