Strojnícky časopis – *Journal of* MECHANICAL ENGINEERING,
VOL 73 (2023), NO 1, 103 - 116

SIMULATION OF A POWER SKIVING GEAR CUTTING PROCESS

HRYTSAY Ihor[1], STUPNYTSKYY Vadym[2], SLIPCHUK Andrii[3]

[1] *Institute of Mechanical Engineering and Transport, Lviv Polytechnical National University, Department of Robotics and Integrated Mechanical Engineering Technologies, Bandery 12, 79013 Lviv, Ukraine, ihor.y.hrytsai@lpnu.ua*
[2] *Institute of Mechanical Engineering and Transport, Lviv Polytechnical National University, Department of Robotics and Integrated Mechanical Engineering Technologies, Bandery 12, 79013 Lviv, Ukraine, vadym.v.stupnytskyi@lpnu.ua*
[3] *Institute of Mechanical Engineering and Transport, Lviv Polytechnical National University, Department of Robotics and Integrated Mechanical Engineering Technologies, Bandery 12, 79013 Lviv, Ukraine andrii.m.slipchuk@lpnu.ua*

Abstract: The results of the computer simulation of the cutting process of gears by the power skiving method are presented. Following the kinematics of the process, a method for generating 3D geometric models of undeformed sheared layers were developed, and their parameters were analyzed. The influence of tool geometry and technological parameters on cutting conditions is investigated. The simulation results and calculation of the tangential force and torque on the tool axis and their influence on the error due to angular elastic deformation of the tool are given.

KEYWORDS: Power skiving, simulation, cutting process, chip geometry, chip compression ratio

1 Introduction

Recently, the process of power skiving, also known as turning teeth lathing, has been widely used to manufacture internal and external spur and helical gears. Thanks to the latest technological developments, in particular, achievements in the field of machine tools, their software, and tool production, this technology has become flexible and efficient, as well as an alternative to traditional methods of gear with a module of up to 10 mm machining. The equipment is both universal multi-purpose five-axis CNC machines and specialized gear hobbing machines. The advantages of this process are high chip removal capacity, absence of idle strokes, and short machining time, as well as the possibility of combining with other methods of forming in one operation.

Features of the power skiving process are high cutting speed and significant forces and moments on the axes of the tool and workpiece. To obtain high machining accuracy, significant machine rigidity is required, as well as a high level of synchronization of tool and workpiece rotation. Violation of these requirements leads to increased vibrations and profile errors of the gears. During the operation of such a wheel in the transmission, these deviations cause a kinematic error, that is, the instability of the transmission ratio, as well as the occurrence of high-frequency oscillations in machine drives.

To avoid these negative phenomena, when developing the technological process, it is necessary to choose in detail the combination of various factors: cutting condition - speed, feed, depth, and the number of passes; machine tool in terms of power and rigidity, in particular, the tool spindle, significantly when cutting planetary wheels; tool geometry and type of protective coatings on its surfaces.

DOI: 10.2478/scjme-2023-0008, Print ISSN 0039-2472, On-line ISSN 2450-5471

To solve such problems, it is necessary to have a methodology that considers many initial factors and describes their influence on the gearing process [1, 2]. There are numerous applied studies of this process to solve such problems. The works [3-8] investigated the cutting process and developed models and software for chip thickness and length calculation and tool design for cutting involute gears. H.J. Stadtfeld develops the design of universal high-speed assembly heads with insert blades and software for this process on a six-axis CNC machine for bevel gears. The power skiving process with high-speed cutters using cemented carbide inserts is performed on 6-axis CNC bevel gear cutting machines. High efficiency and stability of tools with replaceable inserts of stick blade cutters are shown and it is proposed to use skiving for machining both inner and outer wheels instead of hobbing.

The connection of tool geometry and technological parameters with cutting conditions is studied in the work [9]. The influence of coatings and changes in the geometric parameters of the cutting tool on the cutting process are analyzed in the article [10].

In [11] the power parameters of the cutting process are investigated. The works [12, 13] are devoted to studying the design of tools and the influence of their geometric parameters on the power parameters during the machining of gears.

The paper [14] analyzes the influence of process parameters on chip thickness and sliding velocity, analyzes tool wear, and chips welding onto the tooth flanks in a gear-cutting process.

The paper [15] presents an approach for simulating the power skiving process to predict the non-deformed chip geometry as well as the morphology of the produced gear using a CAD system. Based on simulation analysis, a chip thickness can be calculated.

The following features characterize the noted works. Firstly, it is an inaccurate reproduction of the process of kinematics. The cutting motion is formed by a combination of two activities - axial feed and the speed of the main action, which is given to the tool and not to the workpiece, as is customary in these works. Accordingly, the resulting velocity vector will be directed at a different angle relative to the reference surfaces and axes. This is important for correctly determining the tool's cutting forces, friction, and geometric parameters.

Secondly, the shape and dimensions of the transition surface, which is formed in gear teeth gaps in the previous axial position of the device along the feed movement, are not taken into account. At the same time, the actual shape of this surface determines the inner surface of the eliminated chips, shape, and dimensions.

Thirdly, the results of geometric modeling and quantitative parameters of the chips, in particular, the thickness of the cuts, are not used as a basis for further and deeper study of this process, although most of the various force, contact, tribological, and thermal phenomena depend on their values and laws of change of their magnitude in a tool movement.

In these conditions, the task of research and development of adequate models of chip formation, quantification of cut parameters, and calculations of cutting force and torque in the process of power skiving are relevant.

2 Process kinematics

In the process of power skiving, the main cutting motion is achieved by the rotation of the tool in combination with the movement of the cutter along the axis of the workpiece, which occurs due to the inclination of its axis (for spur gears). Auxiliary motions are the tool's axial feed f and the workpiece's circular feed. The vectors of these movements are shown in Fig.1: V_{cut} is the speed of rotational movement of the cutter; V_f is the speed of the tool in the axial

feed, which coincides with the speed of the tooth reduction along the axis of the gear due to the intersection of the axes; V_{gear} is the speed of the gear rotation; V_{Σ} is the speed of the resulting cutting motion.

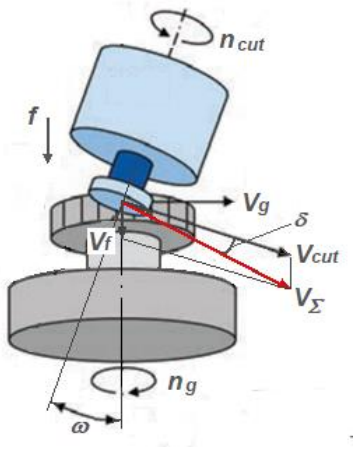


Fig.1. Kinematic scheme of the power skiving process

According to this scheme, the trajectory of the tooth is the geometric sum of the rotational motion vector around the tool's axis and the rectilinear motion along the wheel's axis in axial feed.

Let us establish the relationship between the parameters V_{cut} and V_f. If we bring these values to a standard dimension, then m/min. Based on elementary calculations, we can obtain the following expression for the angle δ between these vectors:

$$\delta \approx actg \frac{f \cdot n_c \cdot \cos\omega}{1000 \cdot V_{cut}} . \quad (1)$$

Taking into account the values of the parameters in this formula, which are used in practice, it can be argued that the angle δ between the vectors of the linear speed of rotational movement of the cutter V_{cut} and the total cutting speed $V\Sigma$ lies in the range of 1-5°, that is, for practical calculations, it can be assumed that they practically coincide. This means that the cutting process, i.e., oblique shear, occurs in the direction of the vector V_{cut} and not in the direction of axial feed, as follows from the schemes presented in the above works. This conclusion change approaches to calculating the cutting force and its components in the power skiving method. Also, it has implications for the determination of the kinematic angles of the tool.

3. Methods of computer simulation of undeformed sheared layers

The following methods were used to form a 3D model of undeformed chips [16-18]. This technique, developed for hobbing, involves representing a continuous generating gear-cutting process in the rolling process by a sequence of discrete cuts. Spatial geometric 3D models of chips were created for all teeth of the active helical surface of the hob, each of which works in a particular zone and eliminates only its inherent chips. These models determine all the necessary parameters of cross-sections of sections and patterns of their change in different phases of hobbing following the kinematics of the process.

A comprehensive research approach is that these parameters serve as the basis for modeling and calculating the magnitude of cutting forces, friction, heat, temperature, and tool wear, modeling oscillations and dynamic processes based on the basic principles of the theory

of metal cutting, as well as for improving the geometry of the tool and choosing the appropriate protective coatings.

Based on this approach and the kinematics described above, an undeformed chip to be cut by a single tooth was simulated. The shape and size of this chip on all cutter teeth for certain cutting conditions will be the same, which is the difference from hobbing.

Given article presents the results of the study for the following initial data: module m = 2.5 - 5 mm; axial feed f = 0.25 - 0.75 mm/rev; the number of wheel teeth Z_g = 40 - 80, number of cutter teeth Z_{cut} = 22-40; angle of rising of the helical line of the cutter ω = 20°; tool speed n_c = 1150 min^{-1}; workpiece material - steel AISI 1040, shear strength [τ] = 300 MPa. Cutting to the full depth of the profile.

Fig. 2 shows the partially formed gaps (a), the contour of the transition surface (b), and the 3D geometric model of the undeformed chip (c). Cutting the allowance with one tooth begins in point 1 and point 2 after the appropriate rotation of the wheel and cutter and displacement of the tool by the axial feed rate. The shape of the chip cross-section is determined by the cross-section of the transition surface (inner chip contour) and the outline of the cutter tooth (outer chip contour).

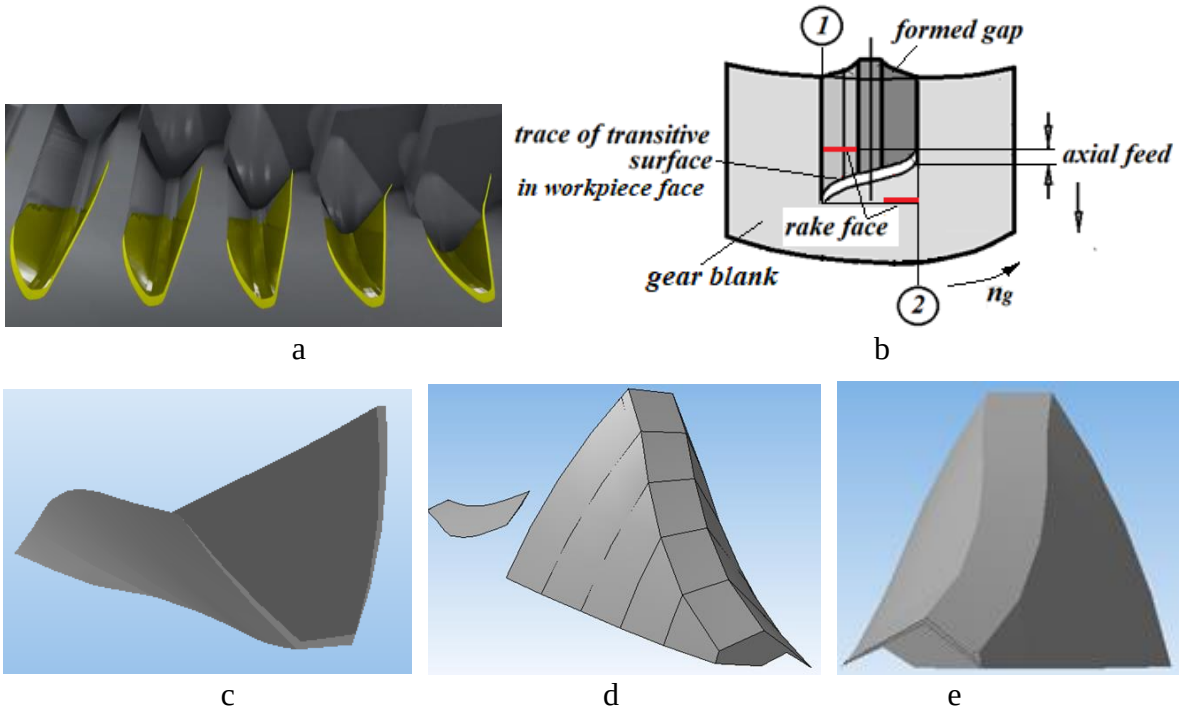


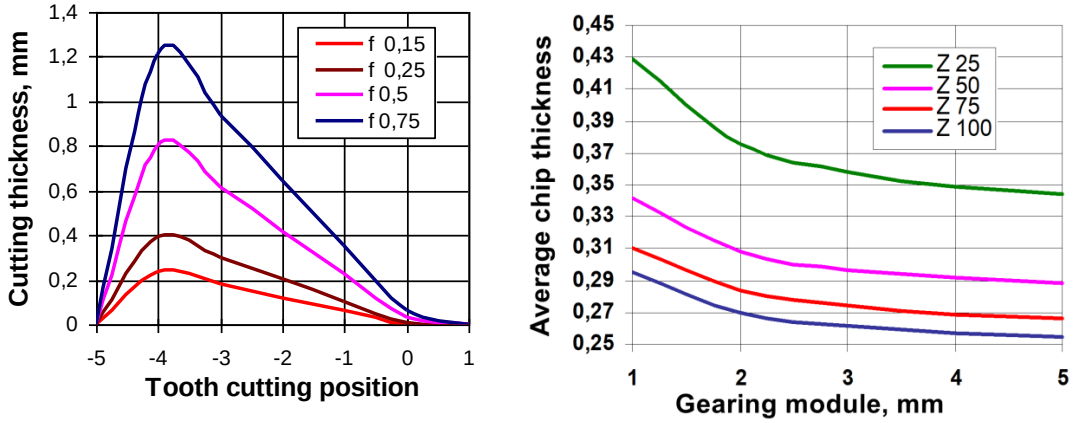
Fig. 2. The partially formed gaps (a), the contour of the transition surface (b), and the 3D geometric model of the undeformed chip (c, d, e). Initial data: m = 2.5 mm; f = 0.5 min^{-1}; Z_g = 60, Z_{cut} = 22; central angle of end overlap of tool and workpiece is 28.6°

4. Parameters of slices

The simulation results for the above data are shown in Fig.2 c, d. The number of discrete tooth positions is 10; the teeth on the leading part are marked as -5...0, and on the trailing part as - 0...+5.

In Fig. 3, a - graphs characterizing the thickness of the slices when changing the feed (a) (module 4.5 mm, number of wheel teeth 60, cutter - 22). The analysis of the obtained results shows that the thickness of the slices depends most of all on the axial feed, less on the number of teeth of the gear and cutter, and insignificantly depends on the module.

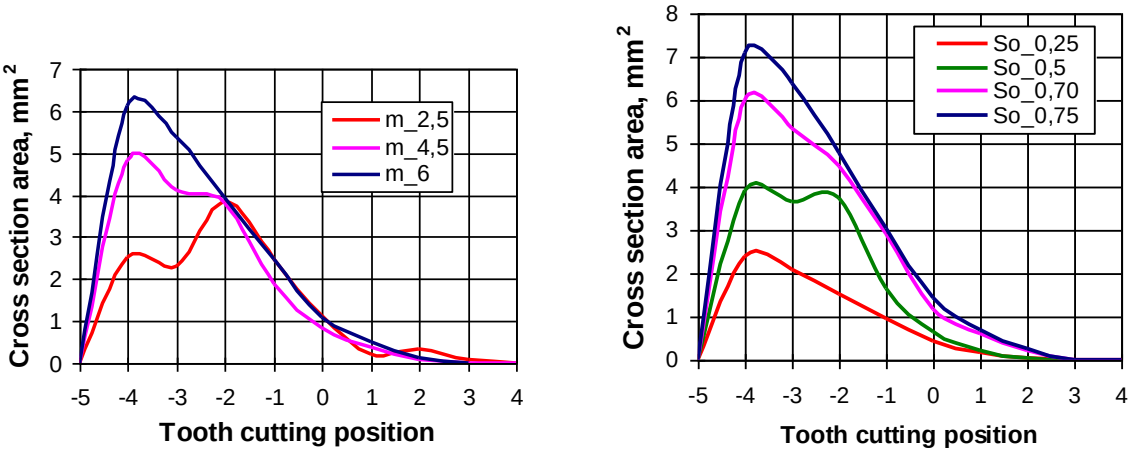
To ensure normal cutting conditions, the radius of rounding of the edges must be less than the thickness of the cut. Otherwise, the allowance will be crumpled, not cut. Based on this, from the graphs in Fig. 3, b - can be found the minimum permissible radius of the rounding of the edges for the following initial data: feed 0.5 mm/rev, module 1 - 5 mm, the number of cutter's teeth is 40, the number of wheel's teeth is from 25 to 100. The criterion for the minimum radius is the average slice thickness.



a b

Fig.3. Thickness of slices depending on the feed (a); the maximum allowable radius of the tool edge rounding (b)

Fig.4, a shows the dependence of the cross-sectional area of the sections on the module, and Fig.6, b - on the axial feed.



a b

Fig. 4. Cross-sectional area of chips

Z_g = 60, Z_{cut} = 22; *a:* f = 0.5 mm/rev; *b:* m = 4.5 mm

5. Kinematic angles of the cutting tool

Due to the inclined positioning of the tool relative to the workpiece, the actual geometry of the cutter is realized. But this change is not constant but occurs by the angle of rotation of the tool. The maximum difference in the value of kinematic (absolute) angles on the blades of the cutter compared to the initial ("basic," "tool" angles) takes place at the entrance and exit and

in the central plane (plane of the centerline perpendicular) these angles correspond to the tool angles that the tool has during its manufacture.

When the tooth starts to contact the workpiece on the leading edge, the actual rake angle is smaller than the base angle, and the flank angle is larger than the base angle. On the trailing edge at this moment of cutting, the opposite change occurs a decrease in the kinematic flank angle and an increase in the kinematic rake angle. It follows from this that at the beginning of cutting on the trailing edge, the cutting force (chip formation force) decreases due to the positive kinematic rake angle, but the friction on the rake surface increases; the cutting force increases, especially after the appearance of traces of wear of this edge. The cutting force is higher near the leading side of the edge, but the friction on the rake face is reduced. The active length of both side edges and the direction of the cutting force in the tooth movement change continuously.

The following dependence was obtained to determine the value of the change in kinematic angles at the initial moment of tooth cutting:

$$\Delta = artg \frac{L_{chord}}{D_{a_cut} \cdot \cos \omega}, \tag{2}$$

where: L_{chord} is the length of the chord corresponding to the central angle of overlap of the cutter with the workpiece at the workpiece face; D_{a_cut} is the outer diameter of the tool; ω is the angle of inclination of the cutter axis relative to the work gear axis.

For example, for the above data (m = 4.5 mm; f = 0.5 mm/rev, Z_g = 60, Z_{cut} = 22, ω = 20°, the change in angles is 3.8°. That is if the tool face rake angle on the side blades is zero, and the back angles are positive and equal to 3°, then the actual rake angle on the leading edge will be -3.8°, on the trailing edge +3.8°; the actual trailing edge on the leading edge is +4.6°, and on the trailing edge -0.8°

The information about the change of kinematic angles makes it possible to form basic angles on their side edges during the manufacture of cutting inserts, which compensate for their change due to the installation of the tool on the gear machine tool, and thus reduce the cutting force and power, as well as increase the tool life.

6. Cutting force and torque on the tool

The diagram of forces in the process of power skiving acting on the rake face of a tooth with a carbide insert is shown in Fig. 5; the rake angle of the insert is zero. F is the friction force on the tool face; P_τ is the shear force; N is the normal force to the face rake; P_o is a component of the cutting force; R is the resultant cutting force.

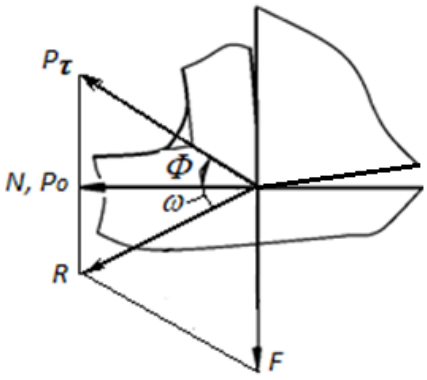


Fig.5. Diagram of loads on the rake face of the cutter

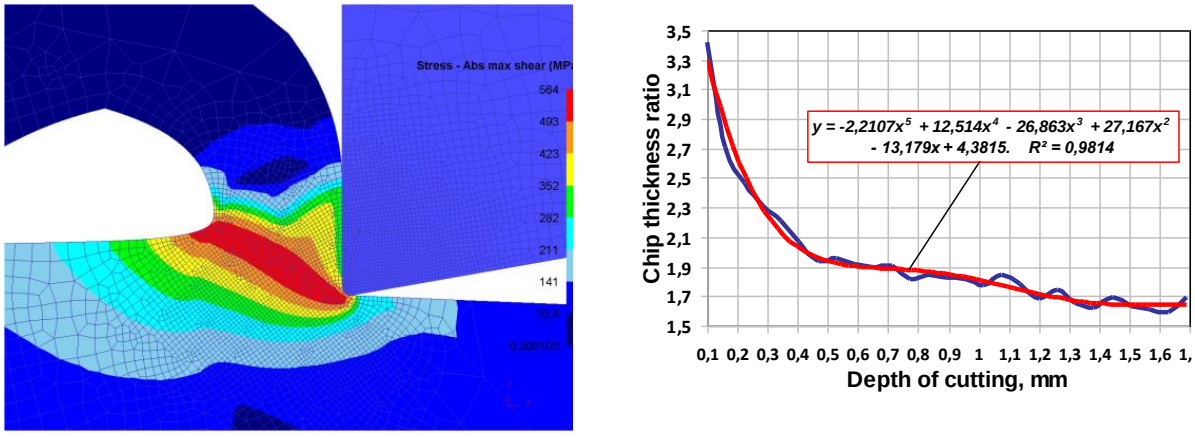
We describe the shear force P_τ as a function of the shear area S_{sh}, mm^2, the shear strength of the gear material $[\tau]$, MPa, and the chip compression ratio ξ (Fig. 5) as follows:

$$P_\tau = [\tau] \cdot S_{sh} \cdot \xi \text{ , N.} \quad (3)$$

The main component of the cutting force P_o, which coincides with the cutting speed will be equal to: where $P_o = P_\tau \cdot \cos\Phi$ is the shear angle. Taking into account that $S_{sh} = \frac{S_{cr}}{\cos\Phi}$, where S_{cr} is the cross-sectional area of the chip, we receive the expression for the force P_o:

$$P_o = [\tau] \cdot S_{cr} \cdot \xi \text{ , N.} \quad (4)$$

To determine if the chip compression ratio is a parameter of the intensity of plastic deformation, a simulation of the cutting process with variable cutting depth in the Deforms 2D was used (Fig. 6, a). With the simulation by this technique, the dependence of the parameter on the thickness of the cut was also established (Fig. 6, b).



a b

Fig.6. Simulation of the cutting process (a) and the graph of the intensity of the chip compression ratio along the slice cut (b)

According to the third theory of strength, the parameter $[\tau]$ is equal to half the tensile strength of the workpiece material.

According to the maximum shear stress third theory, the ultimate shear strength is calculated as half the ultimate tensile strength: For gear wheels made from carbon steels $\overline{\sigma}$ = 600 – 650 MPa, $\overline{\tau}$ = 300 – 330 MPa; for alloyed steels $\overline{\sigma}$ = 900 - 1000 MPa, $\overline{\tau}$ = 450 - 500 MPa.

The cutting in this process is oblique, with a shallow angle of inclination of the cutting edge relative to the cutting speed, and the shear, as shown above, occurs in the direction V_{cut}, close to the resulting total velocity vector V_Σ.

The peripheral component of the cutting force, which acts tangentially to the outer diameter of the cup cutter, creates a torque on the tool axis:

$$T = P_{\text{tang}} \cdot \frac{D_{a_cut}}{2 \cdot 1000}, \text{ Nm}, \quad (5)$$

where D_{a_cut} is the outer diameter of the cutter. According to the diagram of the forces acting on the tool and the workpiece (Fig. 7), the peripheral or tangential force acting on the cup cutter and creating a torque will be equal to from which we obtain:

$$T = \frac{P_o \cdot D_{a_cut}}{2000} \cdot \sin \omega \quad (6)$$

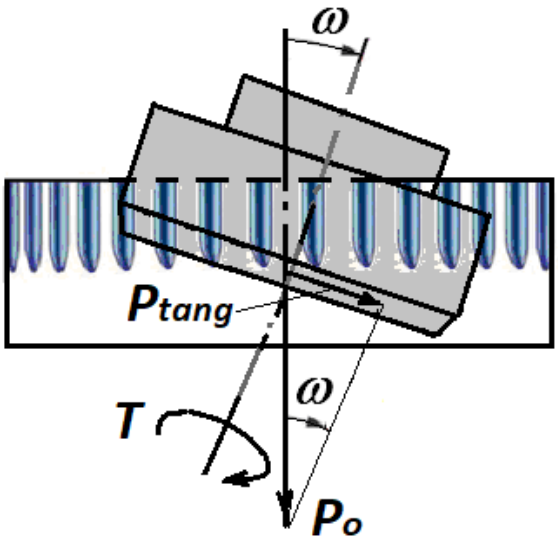
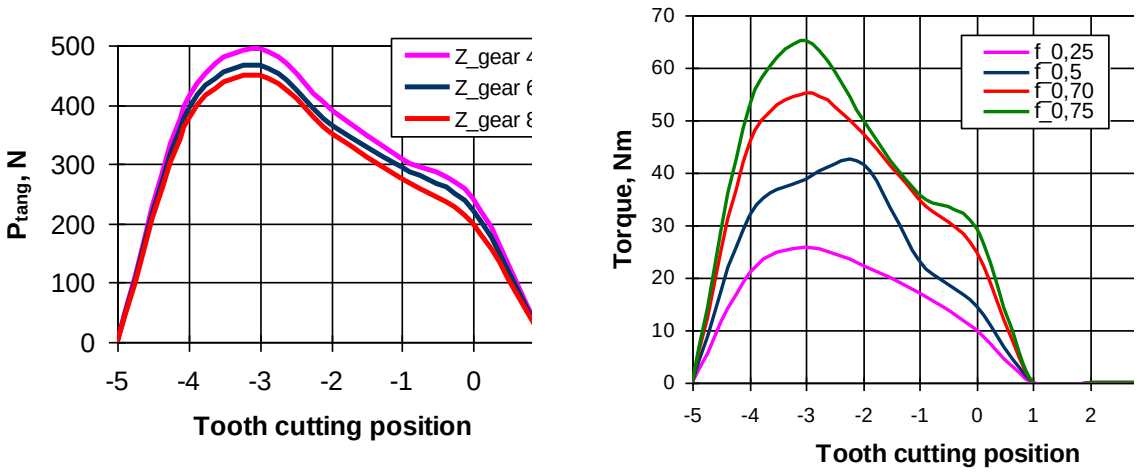


Fig. 7. Forces and torque acting on the tool

Taking into account the above dependences (3) - (6) and obtained based on simulation of the cross-sectional area, chip thickness, and chip compression ratio (Fig. 8, a), typical graphs of changes in cutting force when changing the number of teeth of the gear being cut are shown. Fig. 8, b shows specific torque graphs for different feed rates.



a b

Fig. 8. The main component of cutting force P_o (a) (f = 0.5; m = 6 mm; Z_g = 60) and torque at feed rate change (b) (m = 2.5 mm; Z_g = 40; Z_{cut} = 22)

This process is multi-toothed since several cutter teeth are simultaneously engaged with the work gear, and the system is loaded by the total cutting force, which for each cutting moment can be defined as the instantaneous sum of all forces on the active teeth of the tool. The results show that the cutting power is unevenly distributed along the rotation angle. According to the pattern of energy in single-tooth cutting (Fig. 8, a), Fig. 9 shows a continuous periodic change in the total tangential force, taking into account the multi-tooth contact of the cutter with the workpiece.

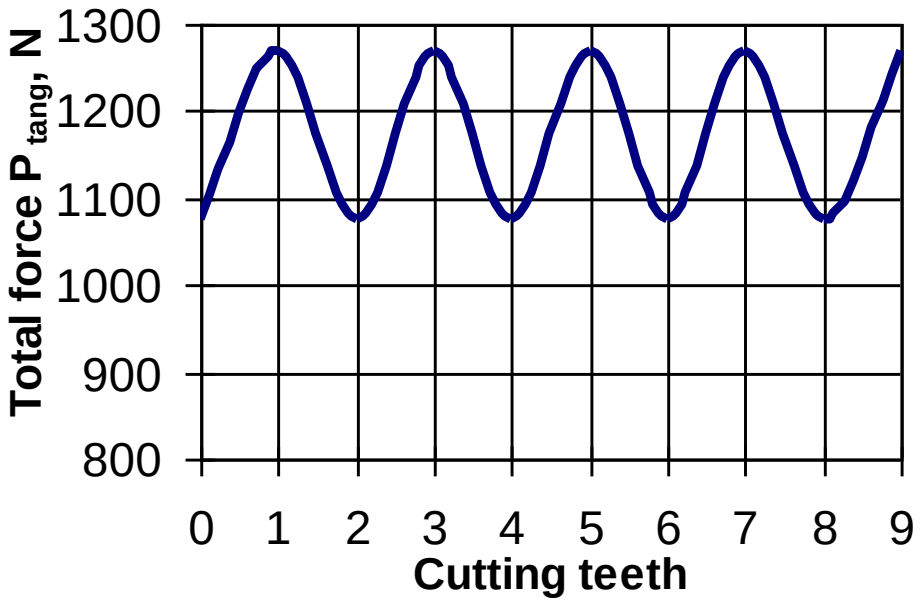
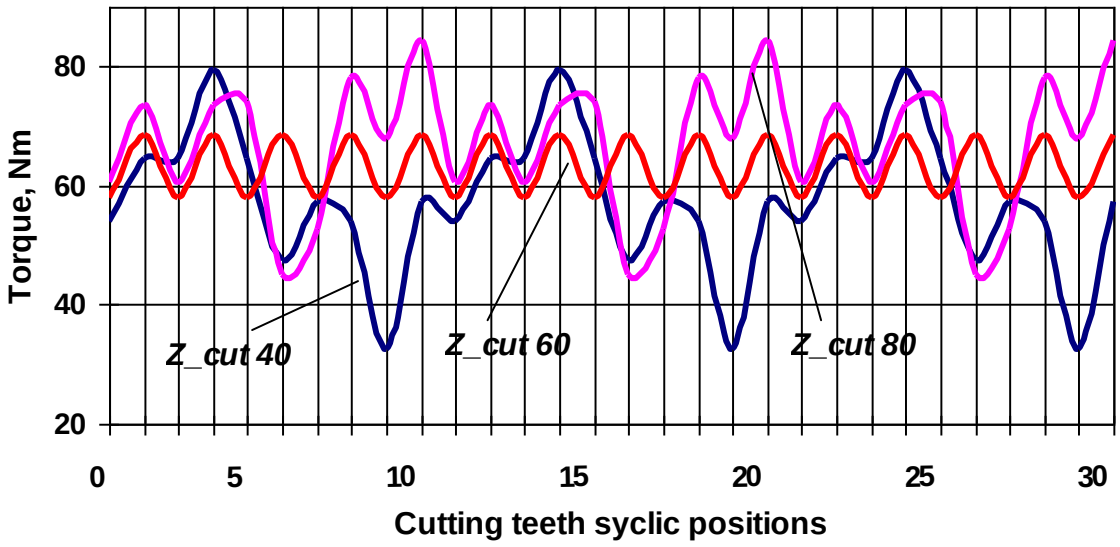
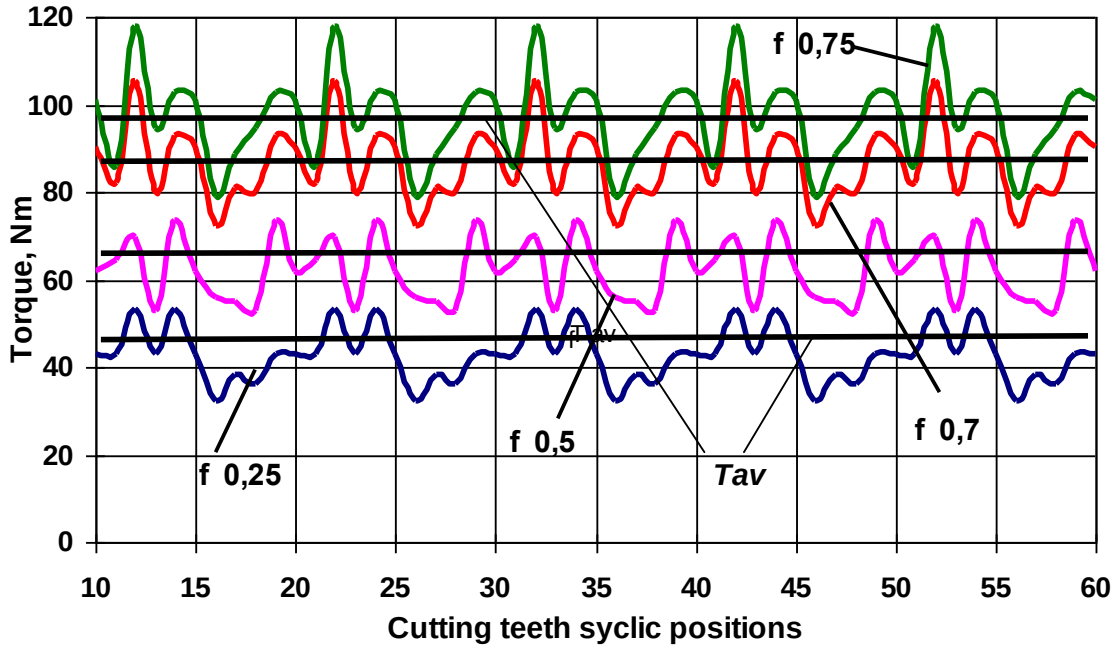


Fig. 9. Total tangential force
f = 0.5; m = 4.5 mm; Z_g = 60; Z_{cut} = 22



a



b

Fig.10. Torques on the tool axis for the different number of wheel teeth (a) and at the various feeds (b): a - f = 0.5; m = 4.5 mm; Z_g = 60; b - m = 4.5 mm; Z_g = 60; Z_{cut} = *22*

In Fig.10 graphs of changes in total torque magnitude on the tool axis for the different numbers of gear teeth (a) and at different feed rates (b) are given.

7. Elastic deformations during cutting.

Due to the multi-tooth engagement in the pair "tool-workpiece," the flexible system of the machine tool is under the influence of conditionally constant (quasi-static) torque and torque fluctuations relative to this average value with a specific amplitude and frequency.

Loading with the average torque on the cutter axis leads to a constant angular error of the cut wheel Δφ. This error characterizes the deviation of the profile, which is equivalent to a change in the meshing angle and leads to a violation of the transmission ratio when such gears and pinions are in transmission operating. Its value is determined by the average torque T_{av} (kN) and depends on the torsional rigidity of the tool spindle of the machine tool J (kN/rad):

$$\Delta\phi = \frac{T_{av}}{J}, \text{ rad.} \tag{7}$$

Periodic changes in the value of the torque within the range of oscillations $T_\omega = T_{max} - T_{min}$ leads to fluctuations in the elastic system and the formation of micro-irregularities on the surfaces of the teeth surface, which, together with the traces of the feed, worsen their roughness. The frequency of these oscillations depends on the coefficient of face overlap and tool rotation speed:

$$\nu = \frac{n_{cut}}{60} \cdot \frac{\phi}{\tau}, \text{ Hz,} \tag{8}$$

where φ is the central angle of overlap of the part with the tool in a gear face, and τ is the angular pitch of the wheel. In the range of speeds and parameters of medium-modular wheels

of external engagement, this frequency is 25 - 100 Hz, and the oscillations belong to low-frequency.

For example, for the following data: m = 4.5 mm; Z_{cut} = 2; Z_g = 60; n =1135 min$^{-1;}$ s_o = 0.5 mm/rev; according to the simulation results we obtain T_{av} = 63 Nm; T_ω = 20 Nm; φ = 26.8°; τ = 16.4°; ν = 31 Hz.

Suppose the torsional stiffness of the tool spindle is 25 kN/rad, then from relation (7). In that case, the static angular error of machining on the outer diameter of the workpiece (corresponding to the diameter of the cutter depressions) will be $2.52 \cdot 10^{-3}$ rad, or 0.14°, and the error due to elastic vibrations will be 0.05°.

Using the results of torque modeling, it is possible to set the requirements for torsional stiffness of the tool spindle of the gear hobbing machine tool depending on the permissible angular error of the equipment in the form of a graph shown in Fig. 11. For example, when cutting a workpiece of alloyed chrome steel with a cutter with a module of 4.5 mm and several teeth 22 with an axial feed of 0.5 mm/rev, so that on a gear of several teeth from 40 to 80 the maximum permissible angular error does not exceed 0.05 radians, the torsional rigidity of the tool spindle should be at least 24 - 28 kN/rad.

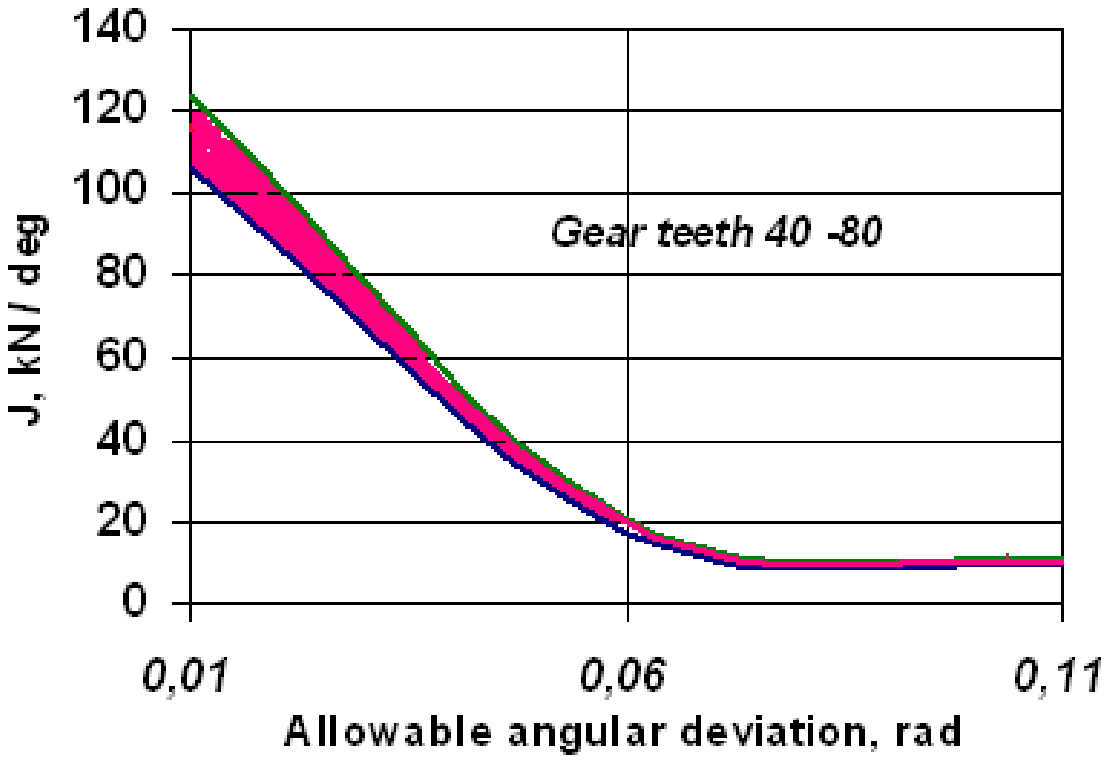


Fig. 11. The boundary zone of minimum rigidity of the tool spindle depending on the permissible angular deviation of the gear profile

CONCLUSIONS

1. The thickness of the cuts on the apex edges is small, so the radius of rounding of the edges of the cutter teeth should be selected, taking into account this thickness for certain initial conditions to reduce the proportion of the process of crushing the allowance by the

rounded top of the edges. The value of the minimum radius, depending on the cutting condition can be established by the method developed in this article.

2. As a result of the intersection of the axes of the tool and the workpiece, the initial geometric parameters of the tool change: the kinematic angles on the edges change along the angle of a tool rotation; such a change adversely affects a cutting force, power, and tool life. To eliminate this negative phenomenon, it is recommended to give the tool angles that compensate for their loss during hobbing according to the method shown in this article.

3. Because the rake face of the teeth is located at a tiny angle to the direction of the cutting speed, the friction conditions between the chips and this surface change: on the leading edges, the friction vector coincides with the cutting speed vector, and on the trailing edges these vectors are opposite, which increases the friction near the side trailing edges and increases the cutting force and power.

4. The creation of a sharp cutting wedge on the teeth reduces their strength, and the increased hardness required for machining wheels of high strength and hardness leads to an increase in the fragility of tool teeth. Increasing teeth strength is possible by choosing the appropriate protective coatings.

5. Due to the uneven removal of the allowance, cutting force and torque fluctuations occur. The frequency of these oscillations lies in the low-frequency range, depending on the cutting speed and the gear ratio in the machine tool engagement of the tool and the workpiece can be from 25 to 100 Hz. Transferred to the workpiece, these vibrations create errors in the gears - static macro deviations of the profile and microroughness. When working in the drive of machines, such variations will make a periodic change in the transmission ratio and increase the friction in the meshing. The developed methodology allows for establishing the requirements for the torsional rigidity of the machine tool from the conditions of a given machining accuracy

6. For wheels with a module of more than 4.5 mm, which are cut in several passes, it is recommended to use different tools for roughing and finishing passes to reduce tooling costs and improve machining accuracy and teeth surface quality. For roughing passes, a tool with straight side edges and sharp apex edges with a positive rake is sufficient since the shape of the tooth face does not affect the accuracy at this stage. Such inserts can be machined on conventional surface grinding machines, reducing tooling costs. The finishing pass must be performed with a precision cutter with the appropriate tooth profile and zero rake angle to obtain the specified gear tooth profile. The problem that arises when changing the tool is the need for precise alignment of the second cutter on the formed gap can be solved thanks to the capabilities of modern machine tool control software systems and precise cutting tool positioning.

REFERENCE

1. Tkach, P., Reviakina, O., Kryvosheia, A., Melnyk, V., Ustynenko, O., Protasov, R. "Meshing Characteristics of Profile Shifted Cylindrical Quasi-Involute Arc-Tooth-Trace Gears. Part 1. Theoretical Base", Strojnícky časopis – Journal of Mechanical Engineering 72 (2), pp. 201 – 210, **2022**. DOI: 10.2478/scjme-2022-0029
2. Bodzás, S. "Tooth Contact Analysis of Helical Gears Having Modified Straight Teeth by Changing of the Number of Teeth on the Pinion", Strojnícky časopis – Journal of Mechanical Engineering 70 (1), pp.1 – 16, **2020**. DOI: 10.2478/scjme-2020-0001
3. Stadtfeld, H. J. “Power Skiving of Cylindrical Gears on Different Machine Platforms”, Gear Technology 1, pp. 52 – 62, **2014**. [online] Available at:

https://www.geartechnology.com/ext/resources/issues/0114x/power-skiving.pdf [Accessed: January/February 2014]

4. Brecher, C., Brumm, M., Krömer, M. “Design of Gear Hobbing Processes Using Simulations and Empirical Data”, presented at 9th CIRP Conference on Intelligent Computation in Manufacturing Engineering - CIRP ICME, Capri (Naples), Italy, 23-25 July **2014**.
5. Klocke, F., Brecher, C., Löpenhaus, C., Krömer, M. “Influence of Tolerances on Characteristic Manufacturing Deviations in Soft Gear Machining” presented at International Conference on Gears, Garching, Munich, Germany, 5-7 October, **2015**.
6. Guo, E., Hong, R., Huang, X., Fang, C. “Research on the cutting mechanism of cylindrical gear power skiving”, International Journal of Advanced Manufacturing Technology 79, pp. 541 – 550, **2015**. DOI: 10.1007/s00170-015-6816-9
7. Guo, E., Hong, R., Huang, X., Fang, C. “A novel power skiving method using the common shaper cutter”, International Journal of Advanced Manufacturing Technology 83, pp. 157 – 165, **2016**. DOI: 10.1007/s00170-015-7559-3
8. Peng Wang, Jingcai Li, Lin Han. “Research on the Cutting Principle and Tool Design of Gear Skiving Based on the Theory of Conjugate Surface”, Mathematical Problems in Engineering 2021, pp. 1 – 13, **2021**. DOI: 10.1155/2021/5469020
9. Hühsam, A. “Modellbildung und experimentelle Untersuchung des Wälzschälprozesses”. Institut für Werzeugmaschinen und Betriebstechnik, Universität Karlsruhe, **2002**. (in German)
10. Bechle, A. “Contribution to process-reliable processing in the high-performance manufacturing process skiving”, Institute for Production Engineering, Karlsruhe Institute of Technology (KIT), Germany, **2006**. (in German)
11. Bodzás, S. “Analysis of the effect of the addendum modification coefficient for contact surfaces of spur gear”, Strojnícky časopis – Journal of Mechanical Engineering 69 (1), pp. 5 – 16, **2019**. DOI: 10.2478/scjme-2019-0001
12. Vorontsov, B., Bosansky, M., Kyrychenko, I., Kuzmenko, N., Stupnytskyy, V., Kuleshkov, Y., Ustinenko, A. “Methods of Designing Gear’s Machining Tools with the Hyperboloid Cutting Part”, Strojnícky časopis – Journal of Mechanical Engineering 70 (1), pp. 135 – 142, **2020**. DOI: https: 10.2478/scjme-2020-0013
13. 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 28, pp. 5107 – 5115, **2014**. DOI: 10.1007/s12206-014-1133-z
14. Klocke, F., Brecher, C., Löpenhaus, C., Ganser, P., Staudt, J., Krömer, M. “Technological and Simulative Analysis of Power Skiving.” Procedia CIRP Volume 50, pp. 773 – 778, **2016**. DOI: 10.1016/j.procir.2016.05.052
15. Tapoglou, N. “Calculation of non-deformed chip and gear geometry in power skiving using a CAD-based simulation”, International Journal of Advanced Manufacturing Technology100 (5-8), pp. 1779 – 1785, **2019**. DOI: 10.1007/s00170-018-2790-3
16. Hrytsay, I., Topchij, V., Kuk, A. “Computer 3D Modelling of Chip Geometry and Force Field in the Hobbing Process”, Ukrainian Journal of Mechanical Engineering and Materials Science, Volume 1(2), pp. 68 – 79, **2018**. DOI: 10.23939/ujmems2018.02.068

17. Hrytsay, I., Stupnytskyy, V., Topchii, V. “Improved Method of Gear Hobbing Computer Aided Simulation”, Archive of mechanical engineering 66 (4), pp. 475 – 494, **2019**. DOI: 10.24425/ame.2019.131358

18. Hrytsay, I., Stupnytskyy, V. “Advanced computerized simulation and analysis of dynamic processes during the gear hobbing”, Advanced Manufacturing Processes. InterPartner-2019. Lecture Notes in Mechanical Engineering 1, pp. 85 – 97, **2019**. DOI: 10.1007/978-3-030-40724-7_9