UKRAINIAN JOURNAL OF MECHANICAL ENGINEERING AND MATERIALS SCIENCE
Vol. 11, No. 1, 2025

Ihor Hrytsay[1], Andrii Slipchuk[2]

[1]Department of Robotics and Integrated Mechanical Engineering Technologies, Lviv Polytechnic National University, Ukraine, Lviv, S. Bandery Street 12, E-mail: ihor.y.hrytsai@lpnu.ua, ORCID 0000-0003-3675-5897
[2]Department of Robotics and Integrated Mechanical Engineering Technologies, Lviv Polytechnic National University, Ukraine, Lviv, S. Bandery Street 12, E-mail: andrii.m.slipchuk@lpnu.ua, ORCID 0000-0003-0584-6104

INFLUENCE OF PROCESS KINEMATICS AND TOOL DESIGN ON GEAR MACHINING BY POWER SKIVING

Received: January 22, 2025 / Accepted: February 25, 2025

https://doi.org/

Abstract. The article presents an alternative approach to the description of the cutting scheme, different from the accepted one, which corresponds to the real kinematics of the Power Skiving process. The interpretation of the process is based on the fact that the main cutting movement is the rotational movement of the tool, which, due to the intersection of the axes of the tool and the workpiece, forms the constructive movement of the face in the direction of the axial feed. In this case, the rotation of the workpiece is an auxiliary movement that does not take part in the cutting process, and the movement of the tool imparted to it by the axial feed is insignificant. The direction of the resulting movement of the cutting speed, which corresponds to such a representation, is at a slight angle concerning the face of the gear being cut. This vector determines the values of the actual or working angles on all three blades of the skiving cutter. These angles significantly change the shearing conditions during cutting, the force on the face, and the friction on the flank surfaces. This scheme has been used to analyze the cutting processes using skiving cutters with different blade designs and geometries and also to describe the negative aspects of combined "Super Skiving cutters."

Keywords: power skiving, process kinematics, resultant cutting speed, working angle, gear cutting, tool design

Introduction

The widespread use of gears as integral components of most modern machines has led to the development of new and improved manufacturing methods and processes. One of the most advanced gear-cutting technologies today is Power skiing. Compared to the traditional gear-cutting methods - gear gouging and hobbing - Power Skiving is characterized by high cutting speeds, short auxiliary passes, high productivity, and gear quality. This method, formerly known as teeth lathing, is being developed in the following areas 1 - improvement of skiving machines: increasing their rigidity, power, vibration resistance, and drive synchronization; 2 - improvement of control systems; 3 - modeling of cutting, forming and related processes and phenomena; 5 - development of skiving tool designs.

The desire to improve this process and eliminate shortcomings has led to intensive tool development. Today, dozens of known types of skiving tools differ considerably in terms of their capabilities and the final result of their use. Under these conditions, gear manufacturers face a dilemma when choosing a particular skiving tool. Given the rapid development of Power Skiving and the fact that it is becoming more and more widespread in gear manufacturing and is being applied to a broader and wider range of products, it is clear that the problem raised in this article is relevant.

Analysis of the state of the art in the industry under study

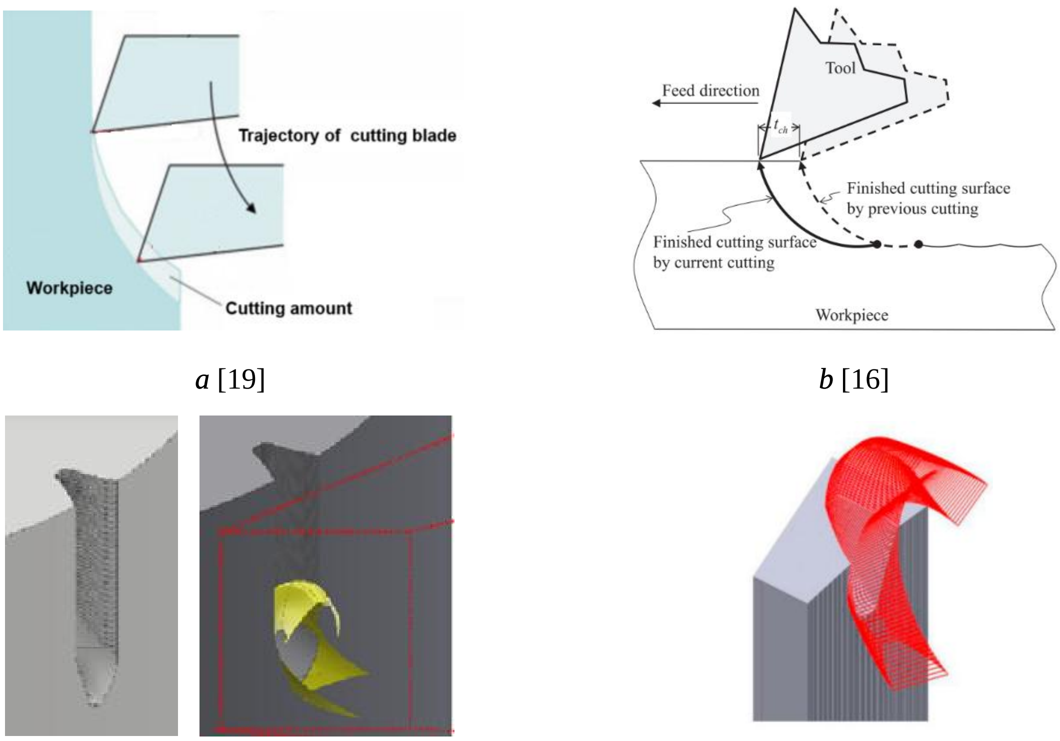
Cutting tools are one of the factors that contribute significantly to achieving satisfactory technical and economic process indicators - machining productivity, accuracy, and product cost. This is particularly true of continuous generation gear processes (rolling cutting principle between cutting tool and workpiece), where the tools used to produce them are increasingly complex. In addition to the requirements for high hardness and strength and thermal stability to counteract wear, these tools must also meet high accuracy requirements, in contrast to single-blade tools. This significantly increases the cost of such tools, both in acquiring and maintaining them in good working order throughout their service life. The problems of studying the Power Skiving process, cutting force, tool life, dependence on many parameters of the initial conditions, and their influence on the gear-cutting process are dealt with in many known works [1-14].

Separate articles [9, 15, 16] investigate the influence of skiving tool parameters, in particular, their geometry (working angle of the cutting edge) and design, on tool life, force, and the cutting process [8, 17-19]. The work [8] is devoted to the description and study of the Power Skiving process, the design of the cutting tool, the analysis of errors in its manufacture, and the modeling of cutting forces and vibrations.

Research Results

1. Kinematic scheme of the Power Skiving. Adequate reproduction of the kinematic scheme of any process is the basis for its modeling and mathematical description. Correct assessment of the set of movements and their overall effect is crucial for determining the values of such factors as the tool's actual (work) angles, on which the intensity of chip formation, cutting force, and other important cutting process parameters depend.

Let's consider how the kinematic scheme of Power Skiving is considered in known studies. A representation of the cutting motion of a skiving cutter is shown in Fig.1. It is represented as the motion of the tool tooth in a plane close to the direction of the workpiece teeth, i.e. close to the motion of the tooth of a hob or disc cutter when cutting a groove.



a [19] *b* [16]

c [20] *d* [5]

Fig.1. A typical illustration of the cutting path of a skiving cutter as used in modern research

This approach is typical of the description of this process in the scientific literature and is used as a basis for modeling (simulation) undeformed chips. The Power Skiving process reproduces the meshing of a pair of gears with transverse axes, i.e., these movements are circular (rotary), as shown in Fig.2, so this approach is incorrect.

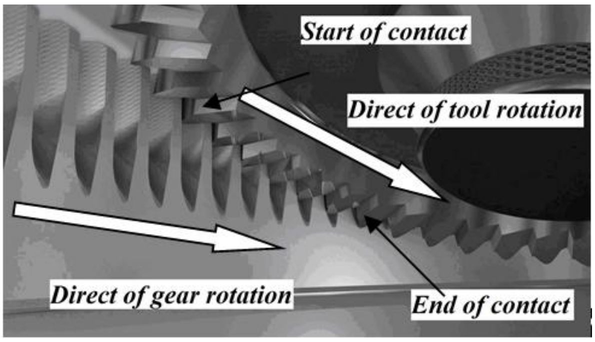
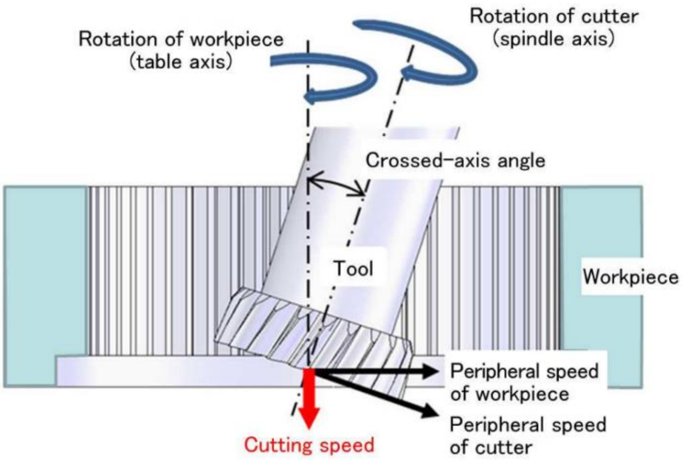
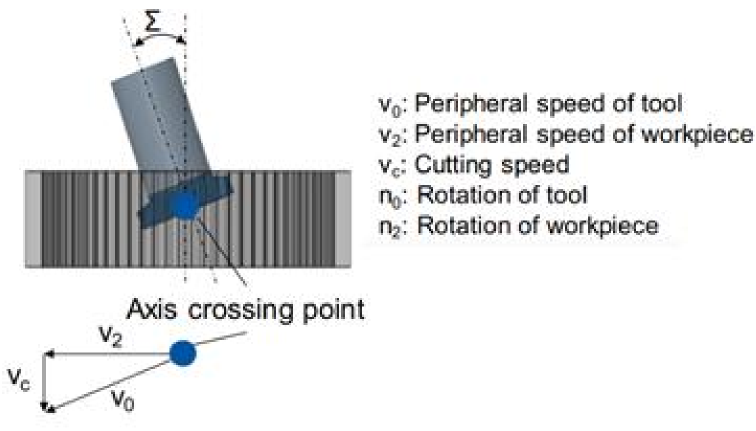


Fig.2. Diagram of cutter and work rotation during Power Skiving gear machining

This misjudgment leads to the following - incorrect interpretation of the cutting speed vector. This is illustrated in Fig.3 where this speed coincides with the axial feed vector.



a [19]



b [21]

Fig.3. Typical interpretation of the direction of the cutting speed in the rotational motion of the tool and workpiece

Let's look at the essence of the incorrect representation of this parameter.

The cutting motion in the Power Skiving process is caused by the cutting teeth face being inclined to the tool's axis of rotation. However, the cutting in the axial feed direction is due to the rotation of the tool. This means that the main cutting motion is the rotational motion of the skiving cutter. The motion of the face in the axial feed direction is a derivative of this motion and plays the role of a constructive motion. A similar phenomenon occurs, for example, in hobbing, where the linear movement of a point on the helical surface of the hob in the axial direction results from the hob rotation, i.e., a constructive movement that participates in the cutting.

Another movement is auxiliary in the form of an axial feed, which makes the process continuous and extends it over the entire length of the cutting path. The resulting cutting speed in the Power Skiving process is, therefore, the vectorial sum of the tool rotation speed V_{tool}, the speed of movement of the tooth face in the axial feed direction V_ω due to the incline of the axes at an angle ω and the rotation of the tool, and the tool speed corresponding to the axial feed V_f.

The value of the parameter V_f, reduced to the dimension of the cutting speed, can be defined as $V_f = 10^{-3} \times f \times n$, m/min. Considering the values of the axial feed used in this process (about 0.5 mm/rev), this speed component can be neglected.

The kinematics of the Power Skiving process, which corresponds to this approach and explanation, is shown in Fig.4.

The speed component V_ω is equal to, $V_\omega = V_{tool} \times \sin \omega$ and its direction coincides with the direction of the axial feed. The cutting speed vector V_{cut} forms an angle λ with the gear speed vector V_{gear} and with the cutting wedge face. From the above, it can be seen that the linear speed of the workpiece is only used to coordinate with the speed of the main movement of the tool; it characterizes the auxiliary movement and does not affect the cutting speed.

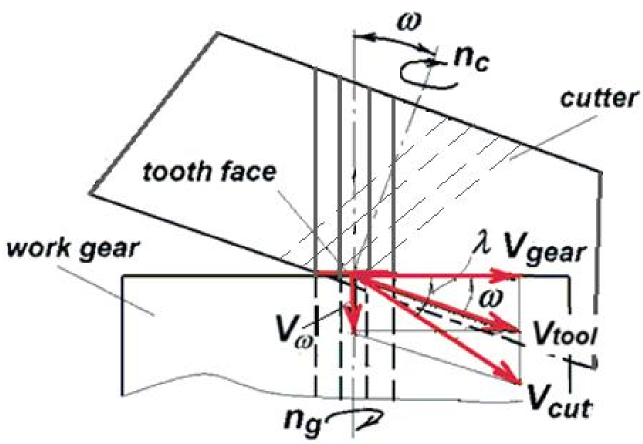
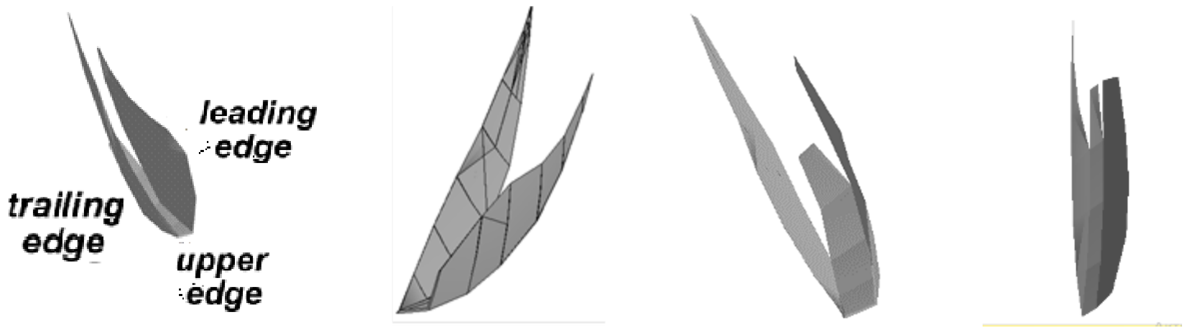


Fig.4. Kinematic diagram of the Power Skiving process, taking into account all cutting movements

The actual (working) angles of the skiving cutter and the cutting conditions on the blades occur in the form of shearing, depending on the direction of the cutting speed, which is characterized by the angle λ . The angles that the blades of the tool have after its manufacture are static or tool angles. After the skiving tool is mounted on the machine, they change - they are actual, working, or kinematic angles, the value of which is calculated relative to the cutting speed vector and not from the base planes of the tool. From the diagram in Fig. 4, we can see that the actual rake angle on the side leading blade becomes negative and changes by a significant amount. This will lead to an increase in the shearing intensity on this blade. The clearance angle on the side trailing blade also becomes significantly negative, increasing friction on the back surface. Both factors cause a significant increase in cutting force and heavy wear on the tips of the teeth.

The working (actual) angles of the skiving cutter blades and the cutting process on the blades take the form of shearing, depending on the angle λ. When machining a gear, each tooth of the skiving cutter works under the same conditions, unlike a hob, where each tooth of its helical surface cuts under different conditions from the other teeth, and each tooth cuts a different shape and chip size. This makes it easier to simulate the Power Skiving cutting process. An example of an undeformed chip cut in a single pass with a skiving cutter is shown in Fig.5. The data were obtained from a model whose design principles are described in the articles [22], they characterize the operation of the different blades of the skiving cutter tooth.



a *b* *c* *d*

Fig.5. Three-dimensional model of undeformed chips during complete machining in one pass in different views

Taking into account the kinematic diagram shown in Fig.4, it is obvious that the actual geometry of the blades of the skiving cutter has a great influence on the process of cutting the gear, significantly changing the conditions of plastic deformation, contact, and friction on the rake and flank tooth surfaces.

2. The influence of tool design and blade geometry on the cutting process. Based on the above, we will analyze how the parameters of different tools affect the cutting process in the Power Skiving method.

Today, many skiving tools have been developed and used in production, which differ in design, geometry of the cutting edge, material, method of fixing and coatings, depending on the purpose. The following types of cutters are known: shank type and mounted (with a central base hole); cylindrical, conical, and disc type - according to the shape of the outer surface; spur and helical; solid and prefabricated; with inserts or replaceable stick blade cutters; with positive and zero face angle on the upper blades, with zero and positive angles on the side blades; with inclination of the upper (main) blade and without inclination; with short and wide crown. Normally, cutters designated "conical" are solid, while "disc" cutters are prefabricated, with replaceable inserts; in most cases, both tool types have a positive clearance angle on the upper blades.

For example, Fig.6 shows solid spur cutters with a positive rake for helical gears (Fig.6, a) and universal helical cutters with oblique faces (Fig.6, b).

a *b*

Fig.6. Solid spur cutters with positive rake for helical gears (a) and universal helical cutter with oblique face (b)

Obviously, with the same initial data, the cutting conditions will be very different when using tools with such significant differences.

For the cutting process, the optimum design is a tapered cup cutter with replaceable inserts, which have a positive rake angle and a positive clearance angle (Fig.7, a, b) and the inclination of the tooth rake face. This universal cutter can be used to cut spur and helical gears. The positive rake angle, as well as the positive clearance angle and face slope, which form a cutting angle and produce an oblique cut, are the most favorable for the cutting process.

The cutter in Fig.7, c is only intended for cutting helical gears since it does not have an inclined face, this angle being formed by the intersection of the axes of the workpiece and the tool. From the kinematic diagram in Fig.4, it can be seen that, with such a design, this tool does not have a V component of the cutting speed, and the cutting process itself is carried out only by the axial feed, i.e., the value V_f. In this case, its productivity will be low.

a *b* *c*

Fig.7. Cutters with replaceable inserts, a positive rake angle,
and a positive clearance angle (a, b) and conical cutter for helical gears (c)

The disk-type skiving cutters shown in Fig.8 have a positive clearance angle but zero rake angle on the upper and side blades, so they will work with higher cutting forces and higher energy consumption than those analyzed above. Solid cutters (Fig.8, b) are cheaper to manufacture, while their cutting qualities are lower than cutters equipped with replaceable inserts, in which the tool materials have higher cutting properties.

a *b*

Fig.8. Conical and cylindrical solid disk-type skiving cutters

Spur cutters (Fig.9, a) are used for finishing. In these tools, the error of the cutting gears is reduced because the gear tooth's direction coincides with the tool teeth' direction. The shape of the tool tooth is involute and symmetrical, but elongated, which reduces the influence of profiling on the error of the cutting gear teeth. The skiving cutter shown in Fig. 9 has a positive rake angle on the upper blades. The cutter's design ensures that the initial geometry - the rake angle after regrinding on the face - is maintained and allows multiple regrinds due to the large width of the tool. The limitation in using such cutters is only helical gears, because only the cutting angle is provided in this case. With this design, there is no vector V_w, so increased processing accuracy is achieved at the expense of productivity.

a *b*

Fig.9. Spur cutter (a) and machining of a helical gear (b)

To increase the efficiency of the process, the developers are working on the creation of non-standard cutters, examples of which are shown in Fig.10, which are defined as "Super Skiving Cutters" [18,19].

a *b* *c*

Fig.10. Conical skiving cutters with helical teeth (a) and straight teeth (b) and cylindrical skiving cutters (c)

Such a design aims to reduce the number of passes by sequentially operating the tool teeth at different heights and levels. The developers predict that their use will make it possible to machine the gear in a single pass. The teeth of the first level, which start cutting, have the smallest height, increasing with each level and corresponding to the crown profile's full height at the last level. It is assumed that the teeth that start cutting form a gap to a small depth, and the teeth of the higher stage continue to cut in this gap as the tool moves in axial feed, increasing the gap's dimensions and approaching the tooth's full height at the exit. This should distribute the material evenly between the teeth, reduce the cutting force and cut the gear in a single pass.

Analysis of the operation of these tools shows the following. Firstly, as mentioned above, Power Skiving cutting takes place during the rotational movement of the tool and gear, so the allowance distribution shown in Fig. 11 [18] does not correspond to the real process. This scheme applies to cutting a groove with a disc cutter and not at all to rotating gear machining.

Secondly, in the case of conical skiving cutters (Fig.10, a, b), the teeth on all levels have the same angular pitch. At the same time, these teeth will have a different circumferential pitch (in mm of arc) because they are formed on different pitch diameters of the tool. This means that these teeth will have a different module, i.e. on a workpiece cut with such a tool, teeth of different modules with different circumferential pitches will be formed. In the best case, there will be an uneven distribution of the allowance on the teeth of higher pitch, but in fact, the depressions formed by the teeth of lower pitch will extend beyond the cutting zone of the teeth of higher pitch.

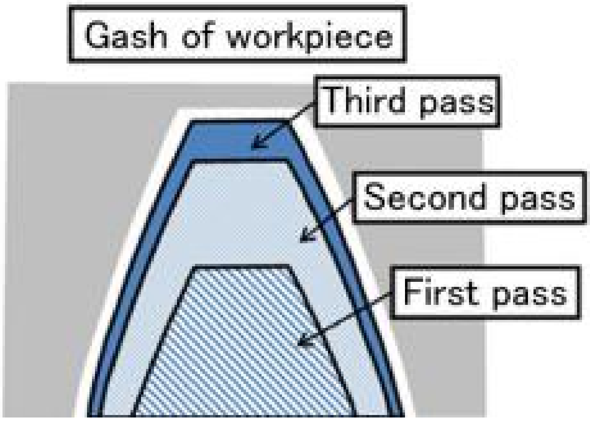


Fig.11. Distribution of stock allowance between three passes in Power Skiving [18]

The main difference in the tool shown in Fig.10, c is that the teeth are not on a conical surface but on a cylindrical surface and have a common addendum circle diameter. At different heights, all the teeth have the same circumferential pitch. As a result, when cutting a gear, gaps and tooth profiles with the same circumferential pitch gradually form on the gear as the cutting depth gradually increases. However, to cut with teeth of different heights, such a cutter must have an additional inclination in another plane, making profiling much more difficult and increasing the tool's cost.

A different approach to separating the teeth of the stock removed from the gap is shown in Fig.12. [19].

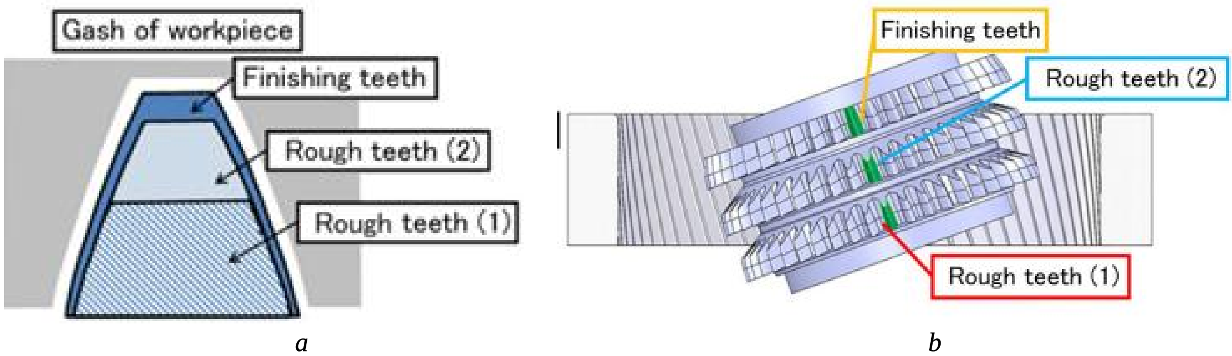


Fig. 12. Representation of the allowance distributed between the teeth of a cylindrical "Super skiving cutter" (a) and a diagram of the machining process (b)

Here, a three-stage tool is proposed to separate the rough teeth by the height of the tooth profile. The idea of such a tool, which consists of cutting the upper and lower parts of the cut teeth separately in two passes, was implemented in 2000 for hobs to produce traction gears of the 8 and 10 mm modules of electric locomotive drives [23-25].

The schemes of the column of the basic rack of the hob for the first (a) and second (b) pass are shown in Fig.13, a. b. The use of such a scheme for the hob made it possible to increase the number of cutting teeth without increasing the addendum circle and to reduce the cutting forces. However, in the case of Power Skiving, using such an approach to design a multi-pass tool will not give the expected result due to the very high cutting forces in two rough passes.

In general, in addition to the above-mentioned drawbacks in the design of "Super Skiving Cutters", they all have high cutting forces in common, especially when machining wide gears. In addition, when the higher tooth starts to cut, it is in contact with the workpiece on a larger diameter, where the gap is still being cut, causing significant shock loads.

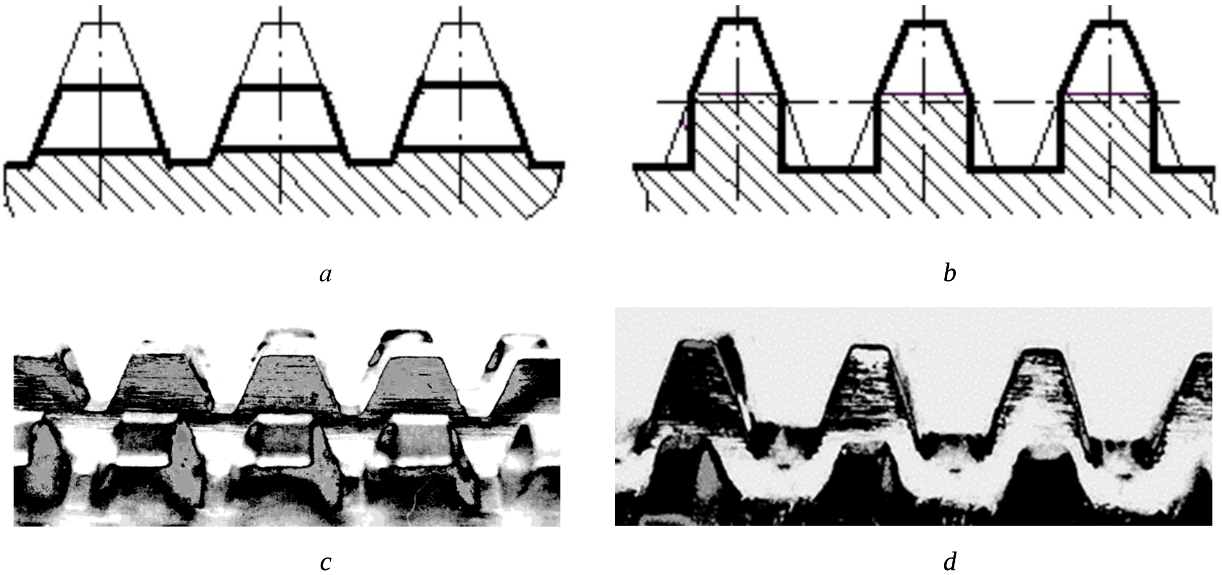


Fig.13. Hob column design (a, b) and photos (c, d) of hobs with split base rack for first (a, c) and second (b, d) pass machining of gears with a large module

Conclusions

A new interpretation of the cutting scheme in the process of machining gears by the Power Skiving method, based on the real kinematics of this process as a set of circular movements, i.e. rotation of the tool and the workpiece, has made it possible to determine the magnitude and direction of the cutting speed as the resulting vector of circular and translational movements.

The vector of the total cutting speed is important for the correct evaluation of the process because, after the installation of the skiving cutter on the machine tool, it receives other values of the angles that characterize the geometry of its blades, defined as real or working angles. The magnitude of these angles is determined by the position of the corresponding surface relative to the cutting speed vector and not by the base surfaces of the tool. For example, if the cutter has a tooth angle of 20°, the total cutting speed vector will be at an angle of 36° relative to the face of the gear being cut. The working angles on the blades of the Skiving cutter significantly affect the machining process, increasing the shear intensity during cutting and the friction on the face and clearance surfaces of the teeth.

This approach made it possible to identify the characteristics of gear machining with different types of skiving cutters currently used in production. In particular, some negative phenomena were identified when using "Super Skiving Cutters" - a possible shift of the gaps about the contour of the cutters at different levels, an increase in the cutting forces, and impacts at the time of cut-in the teeth at each level. The analysis of the operation of ordinary cutters showed their positive and negative characteristics and provided the basis for recommendations for their improvement.

References

[1] K. D. Bouzakis, E. Lili, N Michailidis, O. Friderikos, “Manufacturing of cylindrical gears by generating cutting processes: A critical synthesis of analysis methods”. *CIRP annals*, vol.57, no 2, pp. 676-696. 2008

[2] H. J. Stadtfeld, “Power skiving of cylindrical gears on different machine platforms”. *Gear technology*, vol. 31, no 1, pp. 52-62. 2014

[3] Spath, D., Hühsam, A. “Skiving for high-performance machining of periodic structures”. *CIRP Annals*, vol. 51, no 1, pp. 91-94. 2002

[4] T. Tachikawa, D. Iba, N. Kurita, M. Nakamura, I. Moriwaki, “Basic study on calculation of cutting forces useful for reducing vibration in skiving”. *Journal of Mechanical Design*, vol. 139, no 10, pp. 104501. 2017

[5] F. Klocke, C. Brecher, C. Löpenhaus, P. Ganser, J. Staudt, M. Krömer, “Technological and simulative analysis of power skiving”. *Procedia Cirp*, vol. 50, 773-778. 2016

[6] N. Tapoglou, “Calculation of non-deformed chip and gear geometry in power skiving using a CAD-based simulation”. *The International Journal of Advanced Manufacturing Technology*, vol. 100, no 5, pp. 1779-1785. 2019

[7] V. Schulze, C. Kühlewein, H. Autenrieth, “3D-FEM modeling of gear skiving to investigate kinematics and chip formation mechanisms”. *Advanced Materials Research*, vol. 223, pp. 46-55. 2011

[8] P. McCloskey, A. Katz, L. Berglind, K. Erkorkmaz, E. Ozturk, F. Ismail, “Chip geometry and cutting forces in gear power skiving”. *CIRP Annals*, vol. 68, no 1, pp. 109-112. 2019

[9] H. Onozuka, F. Tayama, Y. Huang, M. Inui, “Cutting force model for power skiving of internal gear”. *Journal of Manufacturing Processes*, vol. 56, pp. 1277-1285. 2020

[10] D. Spath, A. Hühsam, “Skiving for high-performance machining of periodic structures”. *CIRP Annals*, vol. 51, no 1, pp. 91-94. 2002

[11] A. Antoniadis, “Gear skiving—CAD simulation approach”. *Computer-Aided Design*, vol. 44, no 7, pp. 611-616. 2012.

[12] B. Vargas, M. Zapf, J. Klose, F. Zanger, V. Schulze, “Numerical modelling of cutting forces in gear skiving”. *Procedia CIRP*, vol. 82, pp. 455-460. 2019

[13] C.-Y. Tsai and P. D. Lin, “Gear manufacturing using power-skiving method on six-axis cnc turn-mill machining center,” *The International Journal of Advanced Manufacturing Technology*, vol. 95, no. 1-4, pp. 609–623, 2017.

[14] Z. Guo, S.-M. Mao, L. Huyan, and D.-S. Duan, “Research and improvement of the cutting performance of skiving tool,” *Mechanism and Machine Theory*, vol. 120, pp. 302–313, 2018.

[15] M. Jaster. “Skiving: a manufacturing renaissance”. *Gear Technology*. pp. 50-54. 2017.

[16] C. Y. Tsai, “Power-skiving tool design method for interference-free involute internal gear cutting”. *Mechanism and Machine Theory*, vol. 164, pp. 104396. 2021

[17] E. Guo, N. Ren, X. Ren, C. Liu, “An efficient tapered tool having multiple blades for manufacturing cylindrical gears with power skiving”. *The International Journal of Advanced Manufacturing Technology*, vol. 102, pp. 2823-2832. 2019

[18] T. Monden, T. Kikuchi, K. Yoshikawa, N. Fujimura, A. Georgoussis. “Super Skiving Cutter An Innovative Process Modification for Gear Skiving”. *Mitsubishi Heavy Industries Technical Review.* vol. 56, no 1, pp. 1-8, 2019.

[19] Y. Yanase, J. Usude, K. Ishizu, T. Kikuchi, M. Ochi, “The latest gear manufacturing technology for high accuracy and efficiency”. *Mitsubishi Heavy Industries Technical Review*, vol. 55, no 3, pp. 1-7. 2018

[20] P. McCloskey, “Virtual model of power skiving cutting mechanics” (Master's thesis, University of Waterloo). 2019

[21] T. Bergs, A. Georgoussis, C. Löpenhaus, “Development of a numerical simulation method for gear skiving”. *Procedia CIRP*, vol. 88, pp. 352-357. 2020

[22] I. Hrytsay, A. Slipchuk, M. Bosansky, “Justification of the choice of parameters for the gear power skiving operation based on computer simulation”. *Journal of Mechanical Engineering–Strojnicky Casopis*, vol. 73, no. 2, pp. 33-44. 2023.

[23] Zuboriznyy instrument dlya dvokhperekhidnoho narizannya tsylindrychnykh zubchastykh kolis. Pat.45527 A Ukrayiny, B23 F21 // 16 // I. Hrytsay (Ukraine). № 2000042286; Zayavl. 21.04.2000; opubl.15.04.2002, Byul. № 4, kn.1. – S.4-48 [in Ukraine]

[24] I. Hrytsay, I. Aftanaziv, “Pidvyshchennya efektyvnosti dvokhperekhidnoho narizannya zubchastykh kolis cherv″yachnymy frezam z modyfikovanym profilem” [“Increasing the efficiency of two-pass cutting of gears by worm cutters with a modified profile”] // Bulletin of the National Technical University of Ukraine “Kyiv Polytechnic Institute”. Mechanical Engineering. vol. 40. Kyiv, pp. 140 - 149. 2001 [in Ukraine]

[25] I. Hrytsaj, “The theoretical and experimental research of the screw type hobs for two-way cutting of cylindrical cog-wheels of large modules”. *Scientific Research of Universities of Kosice* . vol. 3.. pp. 27-31. 2001