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ANALYSIS OF TOOL DESIGN AND KINEMATICS WHEN MACHINING A GEAR BY POWER SKIVING

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Gears are one of the most common machine parts used for transmitting motion and torque. At the same time, they are among the medium-complexity parts. The reliability and cost of the finished product depend on the manufacturing performance and the quality of the resulting part. Of the various methods of gear machining, power skiving is increasingly being used by the world's leading enterprises. Over the past few decades, it has become a highly competitive gear manufacturing process. This is primarily due to advances in tool engineering and improvements in computer numerical control machines. This article reviews some of the main topics, including new tool designs and insights into process kinematics. This article provides a thorough review of literature and trends in developing new skiving tool designs. It shows a different approach to describing the cutting pattern to the conventional one, which corresponds to the actual kinematics of the power skiving process. During tool operation, the working, kinematic, or actual cutting angles undergo continuous variation. The magnitudes of these angles are governed by the direction of the cutting velocity vector rather than by the initial reference planes of the tool. It has been established that the actual rake angle on the lateral entering cutting edge of a skiving tooth becomes negative and varies along the entire cutting trajectory, thereby increasing the intensity of shear deformation on this edge. A similar effect is observed for the clearance angle on the lateral exiting cutting edge, which also attains a negative value, consequently leading to an increase in frictional forces along the flank surface. The combined influence of these adverse phenomena results in a substantial rise in the cutting force and, more critically, in accelerated wear at the skiver tooth tips. Each group of skiving cutters was analyzed, with emphasis placed on the advantages and disadvantages of each tool type. Taking this scheme into account, cutting processes using skiving cutters with different blade structures and geometries are analysed. The design shortcomings of combined super skiving cutters are analysed.

Keywords: Power skiving, kinematics scheme, cutting speed, undeformed chips, gear, tool design, cutting blade, three-stage tool, cutting angle, clearance angles, skiving cutter, cutter surface, rake angle.

Introduction

Although Power Skiving was patented in the early twentieth century, it remained purely theoretical for almost 100 years. Although researchers attempted to implement it in production from time to time, they were unsuccessful. The biggest problems among them were the insufficient rigidity of the machine tool, the required cutting speed, the lack of synchronisation between the tool and the workpiece, and the insufficient wear resistance of the tool material. The first successful implementation of the method occurred in Japan in the 1960s and 1970s, where it was used to manufacture internal gears. In 2011 the first specialised equipment was presented at the EMO Hannover international trade fair in Germany. Since then, the method has been refined and developed to determine the optimal technology, as well as new tool tooth coatings and designs. Compared to well-known gear machining processes such as hobbing and broaching, Power Skiving has several advantages. First and foremost is the flexibility of this method, which plays a key role in modern production in a highly competitive environment. Unlike hobbing, Power Skiving can be used to cut both internal and external gears. While it comes close to gear hobbing in terms of performance, power skiving is a much more versatile method. Gear hobbing is the most common method of cutting internal gears, but the constant idle significantly reduces the process's productivity. Power Skiving is a high-performance, continuous cutting process that enables the gear to be machined in multiple passes, depending on the module size. The successful implementation of power skiving in enterprises depends on the results of research and the recommendations of tool developers, which are of great scientific interest.

The rapid development and increasing use of Power Skiving in gear manufacturing indicates that the problem discussed in this article is important.

Literature review

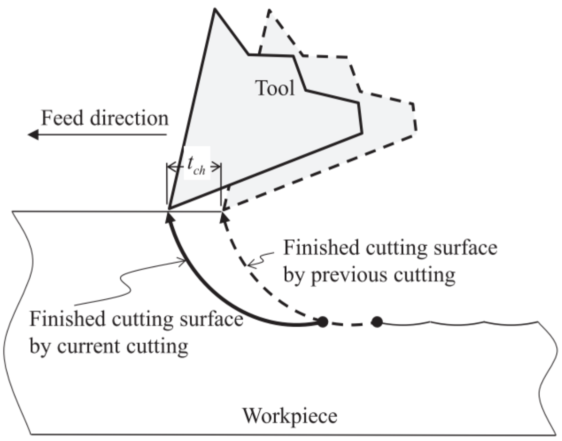
To summarise current trends in the development of the power skiving method, a study focusing on existing scientific literature was conducted. This was chosen as a means of analysing new mathematical models and priority areas that could improve and systematise knowledge about this method. As the analysis of recent literature shows, most scientists are conducting ongoing research into designing tools for Power Skiving. This paper therefore presents an analysis of their results and new proposed models.

Customers must receive high-quality products at reasonable prices. The quality of a cut gear depends on various factors, such as the cutting mode, production costs, productivity, and the rate at which the tool wears down during operation. These parameters are among the most important as they are key to the application and dissemination of the gear cutting method. This study will focus on these two issues. Recently, an increasing number of studies on power skiving have appeared in the literature, either aiming to improve the tool or to understand the kinematics of the process.

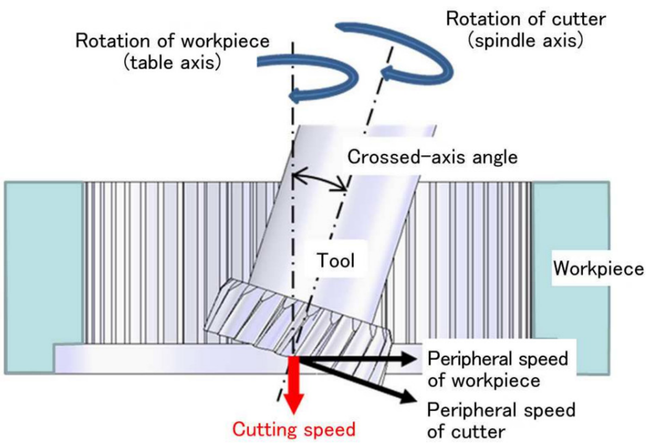
Analysis of typical kinematic diagrams of the Power Skiving process. For the mathematical description of any phenomenon accompanying a particular process, an adequate kinematic scheme is required since the correct assessment of the vectors of the interrelated working movements has an impact on modelling the cutting process. Gear hobbing by power skiving, as well as gear milling with worm cutters, is one of the most complex cutting and shaping processes. Accurately assessing all movements in this process and their mutual influence is crucial for determining the actual (working) cutting angles, which affect tool life, cutting force, and other important parameters of the cutting process:

Due to the complexity of power skiving, researchers often make certain simplifications when reproducing it. One option is to ignore certain elements of kinematics or misinterpret them. Fig. 1 shows the cutting motion of a power skiving cutter, representing the movement of a tool tooth in a plane close to the direction of the gear teeth. This is similar to the movement tooth of a worm gear hob or tooth of a disc milling cutter when cutting a gap.

The authors of [1-4] define the resulting velocity vector as the geometric sum of the linear velocity vectors of the cutter and the machined gear. Consequently, the direction of the cutting speed is represented by a vector that coincides with the direction of the axial tool feed (Fig. 1b). This erroneous judgment leads to an incorrect interpretation of the cutting speed vector. This is clearly shown in Fig. 1b, where the cutting speed coincides with the axial feed vector. This approach is typical of many authors who describe this process in their scientific papers, modelling an undeformed chip and determining all the force parameters.



a[1]



b[2]

Fig. 1 Kinematic diagram for calculating the cutting speed

In another [4], the direction of the axial tool feed is shown to be along the axis of rotation, which is incorrect. In fact, the tool feed is directed along the workpiece's axis of rotation. A common error among researchers of this process is considering the cutting speed to be the sliding speed (Fig. 2).

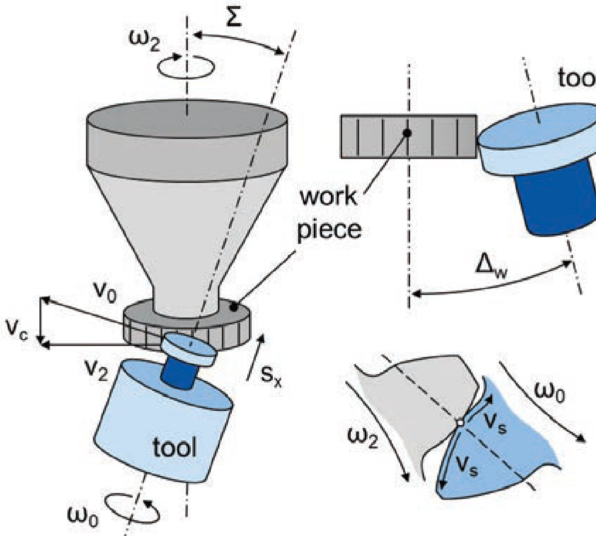


Fig. 2. Schematic representation of velocity vectors in the Power skiving method [4]

Consequently, the erroneous interpretation of kinematics adopted in the above primary sources gives rise to an incorrect assessment of the cutting force and its impact on the process, and an incorrect determination of the actual geometric parameters of the cutting tool and friction forces on its surfaces. It also leads to errors when modelling the volumetric shape of undeformed chips and, consequently, in describing the phenomena that accompany this process. This includes the distribution of cutting force components and their impact on elastic vibrations, machining accuracy, friction, heat, and tool wear.

Analysis of the status of new tool designs in the study. Cutting tools are one of the factors that significantly impact the satisfactory technical and economic performance of the machining process, including its accuracy and product cost. This primarily applies to the processes of cutting gears in continuous generation; the tools used for this process are highly complex. Unlike single-blade tools, they must meet high precision requirements as well as being highly hard, strong and heat-resistant to resist wear. This significantly increases the cost of such tools, both to purchase and to maintain in good working order throughout their entire lifespan. Many well-known works cover the problems of studying the power skiving process, cutting forces, tool life and their dependence on many initial conditions, as well as their impact on the gear cutting process

The significant interest among gear manufacturers in the Power Skiving method as a fast, versatile and flexible gear-cutting process has led to numerous studies aimed at improving the technology and designing more efficient equipment. Most importantly, these studies have focused on finding new cutting tool designs to increase the productivity of this process. Given the challenging operating conditions of the cutter, designing a tool for power skiving is a precise and labour-intensive process that requires special attention to increasing the service life.

An analysis of literature sources shows that most researchers are looking for ways to solve this problem by changing the cutting tool design or determining optimal cutting modes for relevant equipment. Many authors highlight the issue of zero or negative clearance angles during gear cutting [5]. This is because friction occurs between the main flank face of the tool tooth and the newly formed transition surface of the gear, resulting in heat, increased tool wear and reduced cutter life. Several methods to avoid such situations have been described in the literature, such as designing a tapered tool tooth profile or adding an angle to the tool movement.

In paper [6] Stadtfeld investigated the cutting efficiency, chip formation and cutting mechanism of power skiving for machining spur gears, constructing the tooth profile of the tool directly from cross-sections. However, these studies lacked a systematic mathematical model for designing and analysing such tools.

Accordingly, the author of [1] proposes their own method for calculating the cutter tooth design (Fig. 3) in the study.

Chung-Yu proposes a barrel-shaped cutter (Fig. 3). To simplify the calculations, he only considered the area covering the base of the internal gear tooth and the top of the cutting edge of the cutter tooth. The main disadvantage of such a tool is its height and bulk, meaning this cutter can only be used for large-diameter, small-width gears. Unfortunately, the author only provides a mathematical description of the cutter surface and trajectory, and does not present any experimental results. The work is therefore purely advisory with regard to the design of new tools.

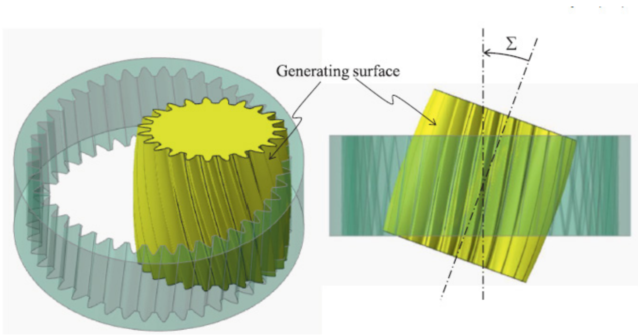


Fig. 3. Schematic illustration of the barrel shape of the tool surface [1]

The relationship between tool geometry and operating modes of the equipment was investigated in [7–9]. By modelling gear turning in a software environment, the authors determined the most effective cutting mode parameters and optimised equipment settings. In addition, based on the results obtained, they attempted to predict the final geometry of the gear. While the conclusions addressed the challenges of tool design in Power Skiving, the authors did not present solutions for an improved design; these works were purely review-based. Significant problems such as the dynamic load on the tool during cutting reducing tool life hinder large-scale industrialisation of the process, prompting inventors to look for new cutter designs.

To overcome these problems, Mitsubishi Heavy Industries, Ltd. conducted comparative tests between its 'super cutter' and a typical tool used by other companies. The article [9] describes the improvement in tool design and cutting pattern in the power skiving method. This paper shows the appearance of a conventional power skiving cutter (PSC) and a newly developed super cutter (SSC). The SSC is a tool consisting of three rows of teeth. The authors first propose dividing the disc cutter tooth by height, using a tool with teeth corresponding to the lower part of the full tooth for the first pass and a tool with teeth corresponding to the upper part of the full tooth for the second pass.

While the authors do not indicate the economic effect of their design, it is evident that machining time was reduced by 40%. For a wear limit of 250 μm, SSC stability is 2.3 times higher than PSC stability for a workpiece with a hardness of HRC 30–35 and 1.4 times higher for HRC 35–40.

Guo et al. proposed even more rows in [5] when developing a newer tool. The proposed cutter (Fig. 3) consists of four rows of teeth arranged one above the other. The operation of the tool teeth begins with the first row, which has the smallest dividing diameter. Then, the teeth of the second row cut into the preliminary transition surface that has been formed, and so on until the teeth of the fourth row begin to cut, according to the broaching principle.

During the experimental studies, several problems arose. Firstly, the cutter teeth are perpendicular, which creates new depressions as the tool is positioned at an angle. Secondly, the load on the tool increases significantly, which endangers both the tool and the equipment. The author himself notes that it is necessary to reduce the feed rate significantly. Additionally, the resulting gear is less accurate when hobbing with such a cutting tool, as is mentioned in the paper.

So, as we can see, the authors investigated the Power Skiving process for various gear cutting applications, primarily focusing on tool improvement or determining optimal cutting conditions [10,11]. Authors [12] based their final conclusions on experimental data or geometric modelling of the process.

Materials and Methods

The proposed kinematics of the power skiving process. In the Power Skiving process, the direction of the cutting movement is determined by the inclination of the front surface of the tool teeth at an angle of 20°–40° to the tool's axis of rotation. Cutting in the axial feed direction occurs due to the tool's rotation. The main cutting motion is the rotation of the cutter and the derivative of this motion is the axial feed movement of the front surface, which serves only as structural movement. A similar effect can be observed in hobbing. Here, too, the linear movement of a point on the helical surface of the worm in the axial direction of the cutter is the result of the worm cutter's rotation. This constructive movement is necessary for the cutting process.

Additionally, axial feed is an auxiliary motion that makes the Power Skiving process continuous. It is performed on the overlapping segment of the gear and tool. Therefore, the resulting cutting speed is the vector sum of the tool's rotational speed (V_{tool}), the front surface speed in the axial feed direction (V_w) due to the crossing of the axes at an angle of w, and the tool's rotation. Take into account the speed of the tool along the gear's axis of rotation, realised by the axial feed V_f. (even if this speed is small in comparison with the others).

It is not difficult to establish the value of the parameter V_f, which is defined as m/min. Given that the axial feed rate is approximately 0.5 mm/rev (depending on geometric dimensions, material, etc.), this component is of little importance. The proposed kinematics of the power skiving process, corresponding to this approach and explanation, are shown in Fig. 4.

According to the compiled kinematic scheme, the velocity component V_w is equal to: . As can be seen in Fig. 4, this component is the only one that coincides with the direction of the axial feed. Consequently, the cutting speed vector V_{cut} is directed at an angle of γ with respect to the gear speed vector V_{gear} and the front surface of the cutting wedge. According to this interpretation, it is only necessary for the linear axial velocity of the workpiece to match the speed of the tool's main motion. This describes the auxiliary motion and does not significantly affect the cutting speed.

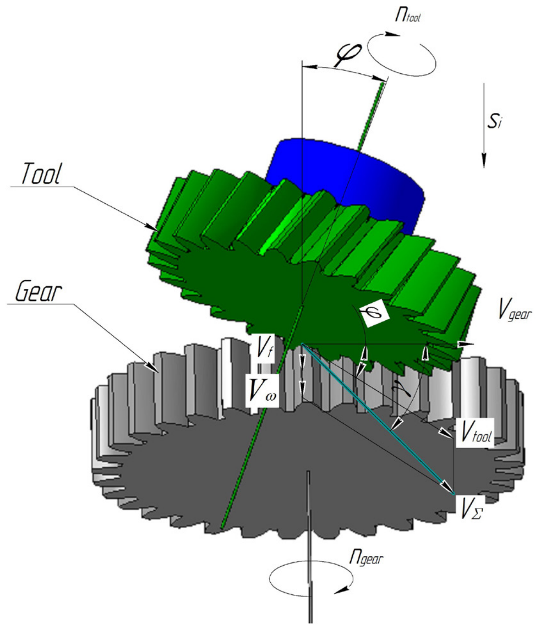


Fig. 4. The proposed actual kinematic scheme of the power skiving process, taking into account all the cutting movements

By determining the direction of the cutting speed, which is directly dependent on the angle γ, the actual working angles of the skiving cutter can be established, as well as the shear cutting conditions on all blades. It is important to distinguish between static or tool angles, which are obtained as a result of tool manufacturing, and working, kinematic or actual angles. Once the tool is mounted on the machine, these angles change during operation — these are the working, kinematic or actual angles. The value of these angles depends on the cutting speed vector rather than the tool's reference planes. Consequently, the real rake angle at the side leead blade of the skiving tooth becomes negative and changes along the entire cutting path. This will lead to an increase in shear intensity on this blade. A similar situation is observed for the rack angle on the original side blade, which is also negative. This leads to an increase in friction on the flank surface. These two harmful processes cause a significant increase in cutting force and, worse still, intense wear to the tips of the cutter tooth.

In the stationary case during gear machining, each tooth of the tool cuts under the same conditions; this is not the case with a worm gear hob, where each tooth along its active helical length cuts under different conditions. The performance of a worm cutter tooth is always variable and never repeatable. From this point of view, it is easier to model the cutting process in the Power skiving process

A detailed review and derivation of a 3D model of an undeformed chip being cut in a hollow is provided in [13] for various cases. In [14], the operation of different blades of a skiving cutter tooth is characterised.

The presented kinematic diagram (Fig. 5) confirms some of the authors' assumptions and modelling results. The geometry of the skiving cutter blades significantly affects the gear cutting process by changing the conditions of plastic deformation, friction, and contact on their front and rear surfaces. When designing new skivers, this factor should be taken into account, and the negative phenomena described should be avoided as much as possible.

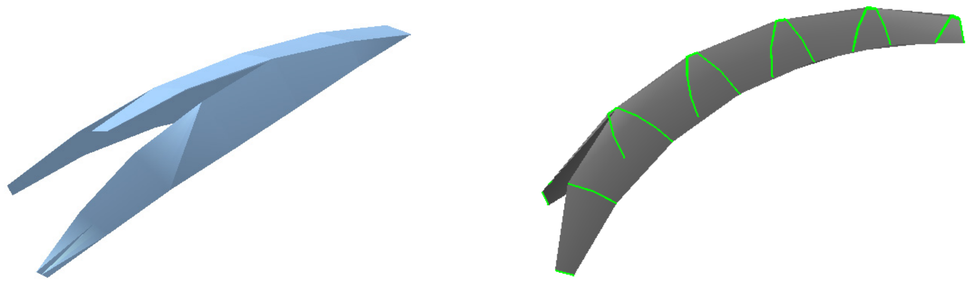
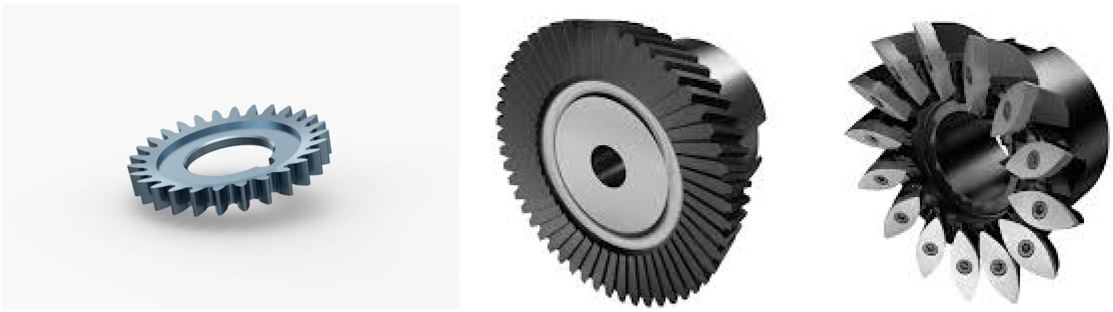


Fig.5. Three-dimensional model of undeformed chips during complete machining in one pass in different views

Results and Discussion

The influence of tool structure and geometry on the gear cutting process. Based on the results obtained, we will analyse how the parameters of various tools affect the Power Skiving method. A significant number of different types of skiving cutter have been developed and are already in use in production, as described in the review. These cutters are classified by purpose and differ in terms of the geometry of the cutting part, design, material and coatings, and method of attachment. Skivers are usually either solid or made of prefabricated inserts with replaceable inserts, as is typical for most cutting tools. Both types of tool have a positive back angle on the apex blade of the skiving tooth.

Fig. 6 shows an example of such a common tool: a solid straight-tooth cutter (Fig. 6a) for manufacturing helical gears, and a helical cutter with a sloping front surface and a positive front angle (Fig. 6 b).



a[15] b[16] c[17]

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

As confirmed by the literature, a tapered cup cutter is preferable for the cutting process. The advantages of a prefabricated cutter with interchangeable inserts that has positive front and rear angles (see Fig. 6. c) are the same as those of any other prefabricated tool, such as a cutter or milling cutter. Although this cutter is more expensive, it only requires inserts to be replaced when they are worn out. It can be used to cut both helical and spur gears. The positive front and rear cutting angles, together with the inclination of the front surface relative to the linear speed vector of the cutter's rotational motion, enable an oblique cut. These are the most favourable conditions for the cutting process.

The cutter in Fig. 6c is designed for cutting helical gears, in which case the cutting angle is formed when the axes of the workpiece and the tool intersect. As can be seen from the kinematic diagram in Fig. 4, with this structure, the tool has no V_w component of the cutting speed and the cutting process is performed solely by axial feed (i.e. V_f). In this case, productivity will be low.

As can be seen in Fig. 7, the disc cutters have a positive back angle and a zero front angle on the apex and side blades. This means that they operate with slightly higher cutting forces and energy consumption than the cutters analysed above. Solid cutters (Fig.7 b) are cheaper to manufacture, but have lower cutting performance than cutters equipped with replaceable inserts made from materials with higher cutting properties.

Cylindrical cutters with parallel or inclined teeth are used for finishing. This is because these tools reduce the error in the gear being cut by ensuring that the direction of the gear tooth coincides with that of the tool teeth. The tool's tooth contour is involute and symmetrical, but elongated, which reduces the influence of profiling on the error of the gear's teeth. The skiving cutter shown in the figure has a positive rake angle on the apex blade. This cutter design ensures that the original geometry — the leading angle — is maintained even after the tool teeth have been resharpened along the front surface. As a result, the cutter is reusable due to its large tool width. These cutters are only suitable for helical gears as the cutting angle can only be achieved in this case. This design also eliminates the cutting speed component — the V_w vector. Therefore, increased machining accuracy comes at the expense of productivity, with finishing operations carried out at low feeds. This operating mode is particularly harmful to the tool because the chip width is small (equal to or approaching the radius at the top of the cutting edge), meaning that no significant cutting occurs along the trajectory. The cutting edges of a tool tooth are subjected to significant frictional forces, temperatures, and plastic deformations.

a[18]

b[19]

Fig.7. Spur cutter (a) and helical cutter (b)

High performance cutter designs. In order to increase the efficiency of the process, non-standard multi-row cutters are being developed, examples of which are shown in Figure 8, which are defined as "super skive cutters". Such designs aim to reduce the number of passes by sequentially operating tool teeth at different heights and levels. The developers expect that they will make it possible to machine a gear in a single pass. The teeth of the first level, which start cutting, have the lowest height, which increases with each level and corresponds to the full height of the tooth crown profile at the last level. It is assumed that the teeth that start the cut form a shallow flute and the higher teeth continue to cut in this flute as the tool moves in axial feed, increasing the size of the flute and approaching full tooth height at the exit. This should evenly distribute the oversize between the teeth, reduce the cutting force and cut the gear in one pass.

Analysis of these tools shows the following. Firstly, as mentioned above, cutting in power skiving is performed with a rotational movement of the tool and gear, so the distribution of the oversize, as shown in Fig.8 [2] does not correspond to the actual process. Such a schematic refers to flute cutting with a disc cutter and is not applicable to rolling gear milling.

a

b

c

Fig.8. Conical skiving cutters with helical teeth (a) and straight teeth (b) and cylindrical skiving cutters (c)

Secondly, in the case of conical skiving cutters (Fig. 8a), the teeth of all planes have the same angular pitch. At the same time, these teeth will have different circumferential pitches (in mm of arc of the circle) because they are formed on different tool diameters. This means that these teeth will have a different modulus, which means that on the gear cut with such a tool, teeth of different modulus will be formed at different heights, with different circumferential pitches. In this case, at best, there will be an uneven distribution of oversize on the higher teeth, but in reality the depressions formed by the lower teeth will extend beyond the cutting zone of the higher teeth.

The main difference in the tool in Fig. 8c is that the teeth are on a cylindrical surface rather than a conical surface and have a common outside diameter. Despite the different heights, all the teeth have the same circumferential pitch. When cutting with a gear, the gear gradually forms depressions and tooth profiles with the same circumferential pitch as the depth of cut gradually increases. However, in order to cut with teeth of different heights, such a cutter must have an additional inclination in another plane, which makes profiling very difficult and increases its cost.

Another approach to the separation of the allowance between individual teeth, which is eliminated by the hollow, is shown in Fig. 8. [2]. Here, a three-stage tool is proposed in which the rough teeth are separated by the height of the tooth profile. The idea of such a tool, which consists of cutting the upper and lower parts of the gear teeth separately in two passes, has been implemented on worm cutters for the production of 8 and 10 mm module traction gears.

In general, in addition to the above-mentioned disadvantages of the "super skiving cutter" designs, all of them have in common high cutting forces, especially when machining large-width gears. In addition, when a superior tooth starts to cut, it comes into contact with the workpiece at a larger diameter, where a cavity is still being cut, causing significant shock loads.

Conclusion

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

The total cutting speed vector is important for the correct evaluation of the process, because after the skiving cutter is installed on the machine, it receives other angle values that characterise the geometry of its blades, which are defined as real or working angles. The value 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 20º, the total cutting speed vector will be at an angle of 36º relative to the end of the gear being cut. The working angles of the cutter's blades have a significant effect on the machining process, increasing the intensity of shearing during cutting and the friction on the front and back surfaces of the teeth.

This approach made it possible to identify the peculiarities of gear machining with different types of skiving cutters currently used in production. In particular, a number of negative phenomena were identified that occur when using "super skiving cutters" - possible displacement of the recesses in relation to the contour of the cutters at different levels, an increase in the cutting forces and impacts at the moment of cutting in the teeth at each level. The analysis of the standard cutters showed their positive and negative characteristics and provided the basis for recommendations for their improvement.

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Аналіз конструкції інструменту та кінематики при обробленні зубчастого колеса методом power skiving

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Зубчасті колеса є одними з найпоширеніших деталей машин, які використовуються для передачі руху та крутного моменту. В одно час, вони відносяться до деталей середньої групи складності. Від продуктивності виготовлення та якості отриманої деталі буде залежати надійність та вартість готової продукції. Серед різних методів обробки зубчастих коліс на світових провідних підприємствах все частіше можна зустріти зуботочіння Power Skiving. За останні кілька десятиліть він став висококонкурентним процесом виготовлення зубчастих коліс. Це пов'язано, перш за все, з прогресом в інструментальному машинобудуванні та вдосконаленням верстатів з числового програмного керування. У даному дослідженні розглянуто деякі з основних тем, а саме: нові конструкції інструментів та нове розуміння кінематики процесу. У цій статті представлено всебічний огляд літературних джерел і тенденції розвитку нових розробок конструкцій інструменту – скайвера. Показано інший підхід до опису схеми різання, відмінний від прийнятого, який відповідає реальній кінематиці процесу Power skiving. Під час роботи інструменту робочі, кінематичні або фактичні кути різання постійно змінюються. Величини цих кутів визначаються напрямком вектора швидкості різання, а не початковими площинами інструменту. Встановлено, що фактичний передній кут на бічній вхідній ріжучій кромці зуба стає від’ємним і змінюється вздовж усієї траєкторії різання, тим самим збільшуючи інтенсивність деформації зсуву на цій кромці. Подібний ефект спостерігається і для заднього кута на бічній вихідній ріжучій кромці, який також досягає від’ємного значення, що, як наслідок, призводить до збільшення сил тертя вздовж задньої поверхні. Сукупний вплив цих несприятливих явищ призводить до суттєвого збільшення сили різання та, що більш критично, до прискореного зносу вершин зубів скайвера. Було проаналізовано кожну групу скайвінг-різців, при цьому акцент зроблено на перевагах і недоліках кожного типу інструменту. З урахуванням кінематичної схеми, проаналізовано процеси різання з використанням скайвера з різною конструкцією та геометрією леза. Проаналізовано конструктивні недоліки комбінованих зубів інструмента. Проаналізовано конструкційні недоліки комбінованих Super Skiving зубів.

Ключові слова: Процес Power Skiving, кінематична схема, швидкість різання, недеформована стружка, зубчасте колесо, конструкція інструменту, ріжуче лезо, триступеневий інструмент, кут різання, задні кути, шліфувальний різець, поверхня різця, передній кут.

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