

## STUDY OF THE KINEMATICS, THE WORKING ANGLES OF THE CUTTERS AND THEIR INFLUENCE ON THE GEAR CUTTING PROCESS BY MEANS OF THE POWER SKIVING METHOD

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**Abstract:** The paper deals with the kinematics of the Power Skiving process, the determination of the total cutting speed, the working angles of the cutting wedge of the Power Skiving tool and their influence on the process of cutting gears. A kinematic diagram of the process is presented which differs from the generally accepted one. The cutting motion and the formation of tooth surfaces are considered to be the result of the combined circular motions of the workpiece and cutter in planes at an angle equal to the angle of inclination of the tool axis. According to this approach, the resulting cutting movement is represented as the geometric sum of the linear speed of tool rotation, the constructive movement of the face resulting from the crossing of the axes in the direction of the axial feed and the axial feed of the tool. The values of the working angles of the power skiving tool relative to the total velocity vector are determined. The influence of the design and geometrical parameters of different cutting tools on the characteristics of gear machining in the process of power skiving is analysed.

**KEYWORDS:** Power Skiving, resultant cutting speed, working angle, gear cutting, tool design

### 1 Introduction

In recent years the Power Skiving process has become increasingly common in the manufacture of gears. Its use began as a replacement for the unproductive gear shaping (gear slotting) that was the main method of cutting internal gears. Due to the high productivity of this method, it was applied to small diameter external gears and then to all types of gears up to 10 mm module. Compared to conventional gear machining methods such as hobbing and gear slotting, Power Skiving is characterised by significantly higher productivity due to its high cutting speed and ensures sufficient machining accuracy due to the high rigidity of the machines and the high synchronisation of the tool and workpiece drives [1-3]. At the same time, it has certain disadvantages, the main ones being the high cost of the tool and its limited tool life, high cutting forces, shock loads and multi-pass cutting, which increases machining time. In order to overcome these negative factors and phenomena, scientific research is being carried out in various directions, much of which is aimed at improving the design of the tool and the kinematics of this process [4, 5]. This makes the problem addressed in this article relevant.

### 2 Literature review

As Power Skiving experience has shown, after the introduction of machines with powerful drives and the development of drive control systems, one of the tasks that arose for the designers was the design of a cutting tool. Numerous publications have been devoted to the study of the design of skiving cutters, their working angles, cutting forces and wear, in which researchers have sought and offered various approaches to improving the tool and the

kinematics of this process. Thus, the articles [1, 6] consider ways of reducing the friction on the surfaces of the cutting wedge caused by zero or negative back angles of skiving cutters.

For example, [7] proposes a solution to this problem by making the tool barrel-shaped, and H. Stadtfeld [3] sees the solution in increasing the angle of inclination of the front face and, consequently, the angle of inclination of the tool shank.

The authors [1, 8, 9] modify the design of the cutters by changing the tooth profile based on the theory of gear engagement in order to increase machining productivity.

There are known works that study the influence of the quality of the tooth profile of the tool on the machining accuracy [4, 10, 11]. In particular, this problem is studied for a tool with a double face and curved blades [12].

The analysis of the known publications shows that a significant part of the research is based on experimental data aimed at obtaining the values of a number of coefficients influencing a particular parameter and clarifying the values of important parameters and process characteristics. Such results can be used only for such data that meet the conditions of the experiment, which limits the scope of their practical use. When developing process models, there are different approaches to the evaluation of the basic assumptions, and the authors use incorrect reproductions of the kinematics of the process. Under these conditions, their conclusions may differ significantly from reality, which reduces the value of such research.

### **3 Research findings**

The main problems in designing a power skiving tool are profiling the teeth and ensuring optimum angles of the tool blades during cutting. Power skiving cutters operate in extreme conditions, where the blades are subjected to significant force and thermal loads caused by intense deformation and friction on the surfaces of the cutting wedge. The result of the combined action of these factors is high cutting forces, increased blade and surface wear, which limits the cutting condition - speed, cutting depth (number of passes) and axial feed.

The kinematics of Power Skiving is based on the meshing of a pair of gears, one of which is a tool whose axis is at an angle to the axis of the gear being machined. This angle provides the cutting action but, as with the meshing of two gears, it causes increased friction on one of the side faces of the tool. The second aspect of the influence of this angle is that the involute profile of the tooth of the power skiving cutter must be formed in an oblique plane which is exactly at this angle to the direction of its tooth. This makes it difficult to calculate the modified fillet profile of the base rack and manufacture the tool, while the accuracy of the gear to be cut depends on it.

The intersection of the axes in this process results in a change in the actual geometry relative to that of the cutter after manufacture, outside the machine tool. The current ISO standard defines two reference systems for tool angles, namely Tool-in-Use (TIU) and Tool-in-Hand (TIH). In the TIU system, the resulting cutting speed is used as the reference base for the angles, while in the TIH system, the tool base and the tool reference plane are used. In the literature there is a definition of "instrumental" or "static" angles, corresponding to the TIH system, and "actual" or "kinematic" angles in the TIU system. In this context, it is necessary first to determine the position of the cutting speed vector and then to determine the working (kinematic) angles on the blades of the skiving cutter.

### 3.1 Kinematic diagram of the Power Skiving process. Definition of the cutting speed vector

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 and 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.

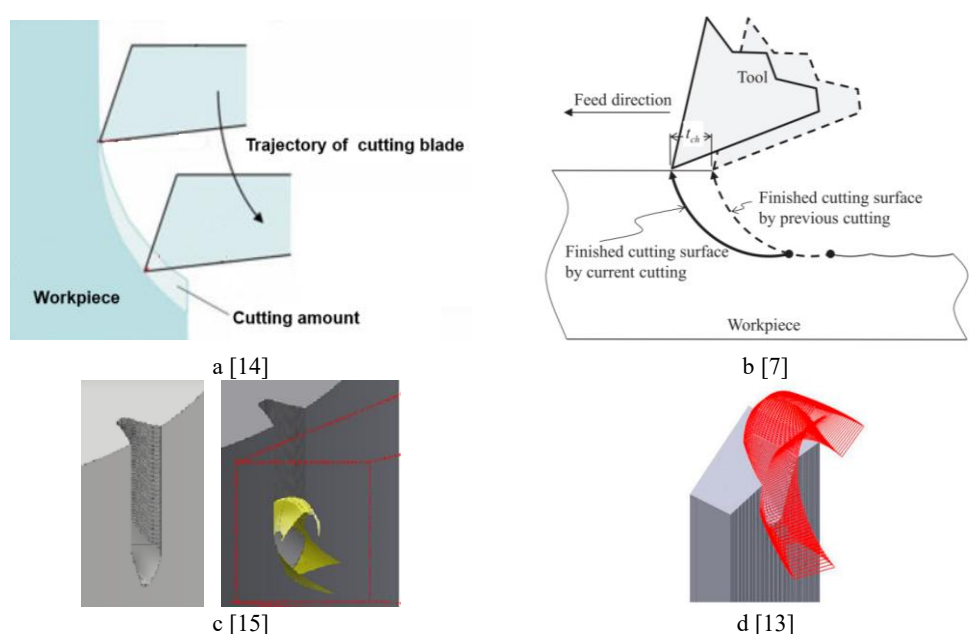


Fig. 1 A typical illustration of the cutting path of a skiving cutter as used in modern research

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. In fact, 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 the Fig.2, so this approach is incorrect. As can be seen from this figure, the cutting and machining of the gap is performed by the rotational movement of the cutter in a plane inclined relative to the gear face by the angle of inclination of the cutter teeth ( $15^{\circ} \dots 40^{\circ}$ ), and not in a plane close to the direction of the gap as shown in Fig. 1.

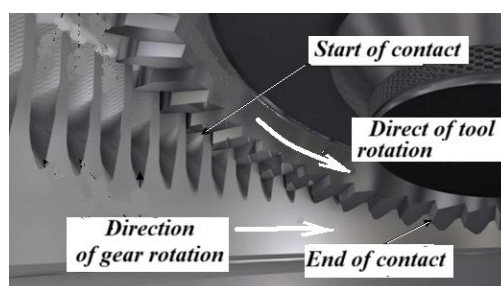


Fig. 2 Diagram of cutter and work rotation during Power Skiving gear machining

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.

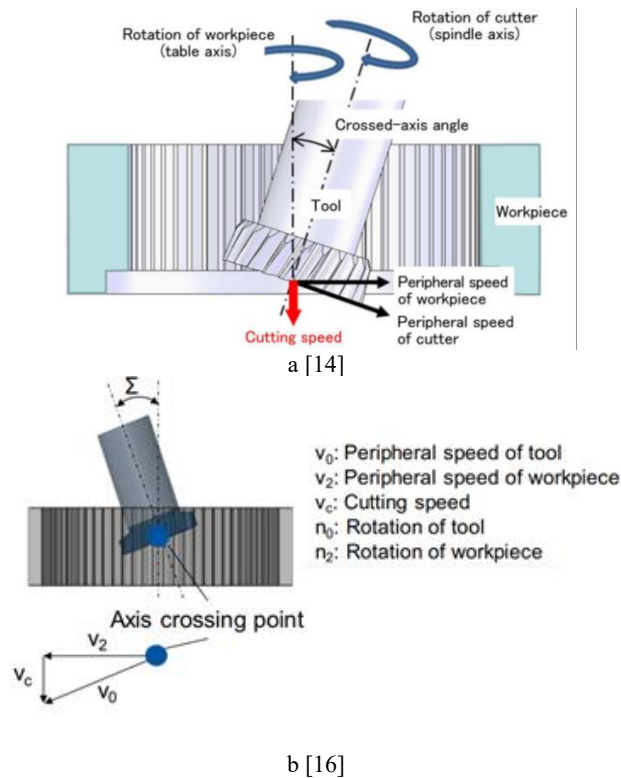


Fig. 3 Typical interpretation of the direction of the cutting speed in the rotational motion of the tool and workpiece

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

As mentioned above, the cutting motion in the Power Skiving process is caused by the face of the cutting teeth being inclined at an angle to the axis of rotation of the power skiving tool, and the cutting in the axial feed direction is caused by the rotation of the tool. This means that the main cutting motion is the rotary motion of the tool, and the motion of the tooth face in the axial feed direction is a derivative of this motion and plays the role of a constructive motion. This can be seen in Figure 4, where as the tool rotates from the "*Start of contact*" point to the "*End of contact*" point, the face is lowered into the gap by the appropriate amount, making the cut due to the inclination of the tool, while at the same time moving in this direction during the axial feed.

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 is the result of the hob rotation, i.e. it is also a constructive movement that participates in the cutting.

Another movement is an auxiliary movement 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  $V_{\omega}$  due to the incline of the axes at an angle  $\omega$  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  $V_f = 10^{-3} \cdot f \cdot n_c$ , m/min, where  $n_c$  – tool rotation speed,  $\text{min}^{-1}$ ,  $f$  – axial feed, mm/rev. Taking into account the values of the axial feed used in this process (about 0.5 mm/rev), this component of the speed 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  $V_\omega$  is equal to  $V_\omega = V_{tool} \cdot \sin \omega$  and its direction coincides with the direction of the axial feed. The cutting speed vector  $V_{cut}$  forms an angle  $\lambda$  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 characterises the auxiliary movement and does not affect the cutting speed.

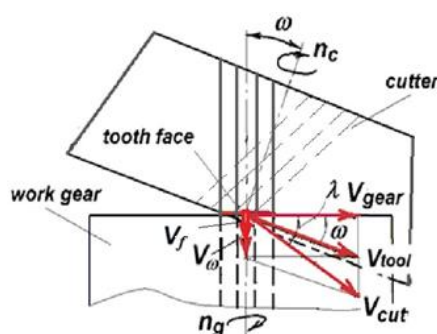


Fig. 4 Kinematic diagram of the Power Skiving process, taking into account all cutting movements

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

Let us represent the vectors that characterise the movements of the tool and the workpiece in the form of scalar segments (Fig.5), from which we can write:  $OC = \sqrt{OA^2 + AC^2}$ .

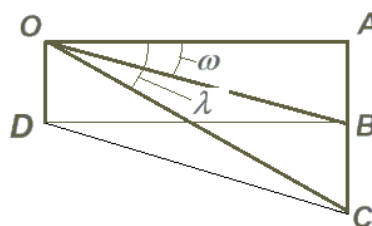


Fig. 5 Relationship between components characterising the cutting motion

Since, as defined above,  $OA = V_{tool} \cdot \cos \omega$ ,  $AB = OD = BC = V_{tool} \cdot \sin \omega$ , and  $OC = V_{cut}$ , we have the following result for the determination of the actual cutting speed:

$$V_{cut} = V_{tool} \cdot \cos \omega \cdot \sqrt{1 + 4 \cdot \tan^2 \omega}, \quad (1)$$

where  $V_{tool} = \frac{\pi \cdot D \cdot n_c}{1000}$ , m/min:  $D$  - tool diameter, mm;  $n_c$  - tool rotation speed,  $\text{min}^{-1}$ .

For example, if the linear speed of the tool on the spindle is 200 m/min, the angle of intersection of the axes is  $20^\circ$ , then the cutting speed will be 287 m/min, which corresponds to a spindle speed of 637 rpm with a tool diameter of 100 mm.

On the basis of the data obtained, after the appropriate transformations, the angle  $\lambda$  will be equal to:

$$\lambda = \arctg \frac{AC}{OA} = 2 \cdot \operatorname{tg} \omega \quad (2)$$

For example, if the angle of intersection of the axes of the tool and the gear is  $20^\circ$ , then based on the dependencies (1) and (2), the angle between the speed vector and the front face of the tool will be  $36^\circ$

### 3.2 Working or kinematic angles of the skiving tool

Based on the above, we determine the working angles of the tool, which characterise the position of the face and flank surfaces of the cutting wedge in relation to the cutting speed.

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 size of chip. This makes it easier to simulate the Power Skiving cutting process. An example of an undeformed chip cut in a single pass with a power skiving cutter is shown in Fig.6. The data were obtained from a model whose design principles are described in the article [17, 18], they characterize the operation of the different blades of the power skiving cutter tooth Fig. 2. Cross-sectional area (a-c) and cut thickness (d-g) at different cutter tooth/shaft set angle

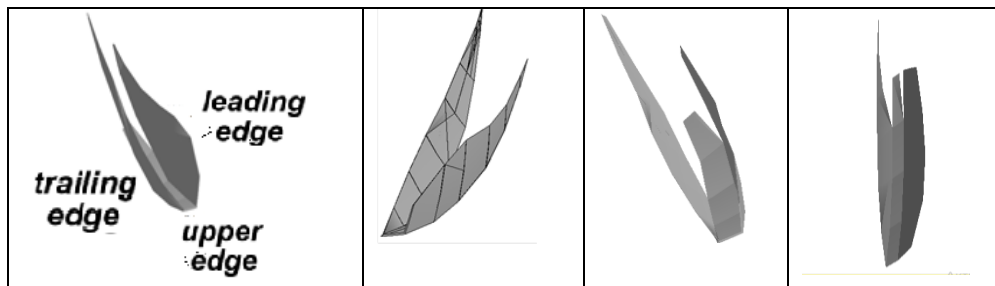


Fig. 6 Three-dimensional model of undeformed chips during complete machining in one pass in different views [17]

From the geometric model of the chip it follows that in Power Skiving all three cutting blades and their working angles will have the same effect. Let us consider the geometry of the cutting wedge of a spur skiving cutter. Here and in the following we will not use the term geometry to refer to the design of the tool, but to the angles of the tool. Consider a cutter in which the upper and side blades, which share a common front face, have a face angle of zero, the clearance angle on the upper blade is positive, within  $5^\circ$ , and the clearance angles on the side blades are zero (Fig.7). The static or tool angles of the tooth of the Power Skiving cutter (corresponding to the TIH system) are shown in Fig.7 and the working angles of the cutter in the TIU system are shown in Fig.8.

Here  $\gamma$  and  $\alpha$  are the face and clearance angles of the tool in the TIH system,  $\gamma_{work}$  and  $\alpha_{work}$  are the working angles in the TIU system on the corresponding blades. The angles  $\gamma$  and  $\alpha$  are in the main section planes of the blades, which are perpendicular to the tooth face and to the side faces of the corresponding blades near the tooth tips, within the active width of the cut. The main cutting planes: 1-1 - upper blade; 2-2 - leading side blade and 3-3 - trailing side blade. In the figure:  $r_f$  - rake face;  $f_f$  - flank (clearance) face on the corresponding blades.

From the scheme of speeds that make up the kinematics of Power Skiving (Fig.4), it follows that the cutting process for the upper blade is oblique, with the angle of inclination of the blade relative to the cutting speed equal to  $\lambda$ , while the change in the face and clearance angles of this blade relative to the cutting speed will be insignificant [19]. Unlike the upper blade, the angles of the side blades in the TIU system change significantly.

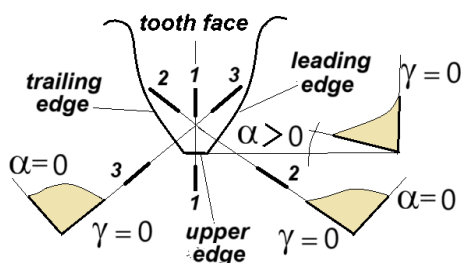


Fig. 7 Diagram of angles on the blades of the power skiving cutter tooth in the TIH coordinate system

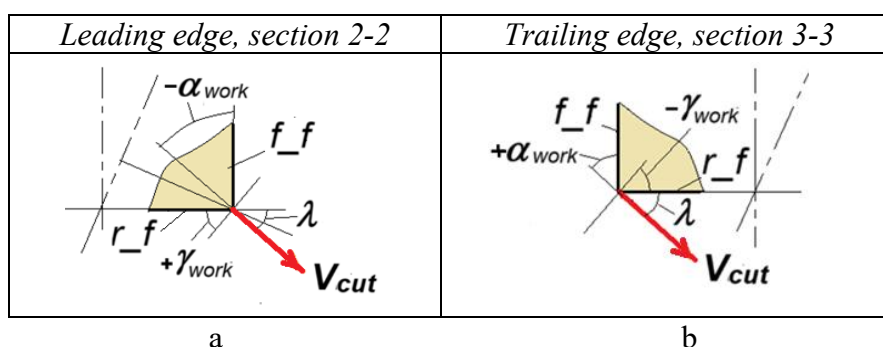


Fig. 8 Working angles on the leading (a) and trailing (b) blades of the skiving cutter in the coordinate system TIU

On the leading side blade, the face working angle becomes positive, equal to  $90^\circ - \lambda$ , and the clearance angle on this blade has the same value, but with a minus sign:  $-(90^\circ - \lambda)$ . On the trailing blade we have the opposite results: the leading angle is negative with a value of  $-(90^\circ - \lambda)$  and the trailing angle is positive with the same value of  $90^\circ - \lambda$ . For example, if the angle of inclination of the tool shaft is  $20^\circ$  and the angle of the resulting speed vector is  $36^\circ$ , we will have on the leading blade  $\gamma_{work} = 54^\circ$  and  $\alpha_{work} = -54^\circ$ , and on the trailing blade  $\gamma_{work} = -54^\circ$  and  $\alpha_{work} = 54^\circ$ .

The kinematics in Fig. 4 fixes the position of the tool and the part in the central plane, where the direction of the tool tooth coincides with the direction of the gear gap. However, in other angular positions of the tool tooth - from the "Start of contact" point to the "End of contact" point in Fig. 2 - such a coincidence will not occur and the tool tooth will have a certain inclination relative to the direction of the gap in which it cuts. This means that the value of the angle  $\lambda$  will be slightly different from the value calculated using formulae (1) and (2).

The following conclusions can be drawn from the results obtained:

- calculations show that at the moment of the beginning of the contact of the tooth of the skiving cutter with the workpiece and at the moment of the tool leaving the contact in the rotational movement of the blade, the values of the angle  $\lambda$  will vary within  $3^\circ \dots 5^\circ$ . Accordingly, at the point of "start of contact" on the trailing blade, the face angle will increase and will be equal to  $51^\circ \dots 48^\circ$ , which will improve cutting, and on the leading blade at the

point of "End of contact", the clearance angle will change to  $-57^{\circ} \dots -59^{\circ}$ , which will increase friction on the flank surface;

- on the leading blade, the shear intensity will decrease, but the friction on the flank surface will increase; on the trailing blade, the shear intensity will be greater, but the friction will decrease;

- it follows that the wear on the leading blade will be concentrated on the clearance surface and this will be the result of increased abrasive friction. On the trailing blade, the cause of wear will be a significant shear force and the wear area near this blade will be on the face;

- increasing the angle of inclination of the tool axis increases productivity by increasing the  $V_{\omega}$  component of the total cutting speed, but also significantly increases the cutting force due to two factors: an increase in the cutting compression ratio (which is the chip thickness divided by the depth of cut, on the trailing blade) and friction on the flank surface (on the leading blade).

- it should be noted that the calculated value of the angle  $\alpha_{work} = -54^{\circ}$  on the leading blade does not take into account the fact that the cutting process takes place with simultaneous rotation of the tool and the gear, which largely eliminates the negative effect of this angle on the friction on the clearance surface of the leading blade.

#### 4 The influence of tool design and geometry on the Power Skiving cutting process

Based on the above, we will analyse how the parameters of different tools affect the cutting process.

Today, a considerable number of power skiving tools have been developed and are in production, varying in design, edge geometry, material, fixing method and coatings, depending on the application. The following kinds of cutters are known: shank type and mounted (with a central base hole); cylindrical, tapered (conical) and disc type - according to outer surface shape; spur and helical; solid and prefabricated (Fig.9), with replaceable inserts or stick blade cutters; with positive and zero rake angle on the upper blades, with zero and positive angles on the side blades; with and without inclination of the face plan; with short and wide crown. It is obvious that with the same initial data, the cutting conditions will be very different when using tools with such significant differences.

Cutters, defined as "tapered" and "disc", usually have a positive rake angle at the upper edge and can be either prefabricated, with replaceable inserts, or solid.



Fig. 9 Solid cutter (a) and cutter with inserts (b)

From the point of view of the cutting process, the optimum design is a conical disc cutters with inserts, which has a positive face and clearance angle (Fig.10) and also an angle of inclination of the face of the tooth (Fig.10, a). This cutter is universal and can be used to cut both spur and helical gears. The positive angles of the face and flank surface and the

inclination of the face with respect to the vector of the linear speed of the cutter's rotation, which forms a cutting angle and produces an oblique cut, is most favorable for the cutting process.

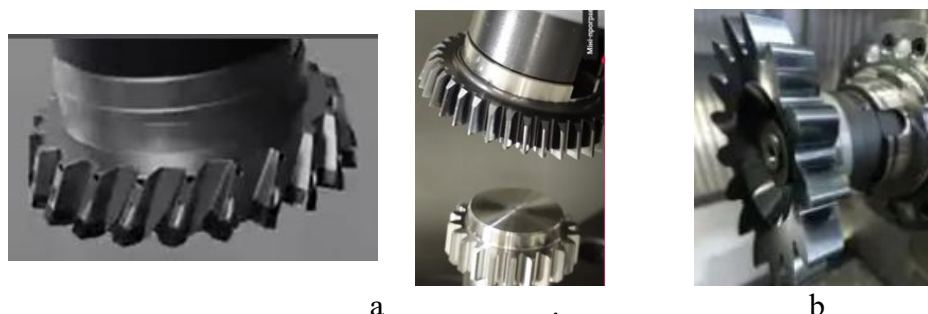


Fig.10 Disc cutters with inserts (a) and solid cutter (b)

The conical straight-tooth cutter in Fig.10 b is only intended for cutting helical gears, as it does not have an angle of inclination on the 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 has no component  $V_\omega$  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.

This is also typical of the tools shown in the Fig.11 - spur skiving cutters for finishing. The teeth on these tools have an involute profile that matches the profile of the teeth on the gear they are cutting. The advantage of such a tool is that it can be manufactured as a gear by standard methods, e.g. hobbing followed by grinding after heat treatment. A positive rake angle can also be easily achieved and maintained after regrinding. The only limitation to the use of these cutters is the use of helical gears, as this is the only way to obtain the cutting angle. As mentioned above, these cutters also lack the vector  $V_\omega$ , so the increase in machining accuracy is achieved at the expense of productivity.

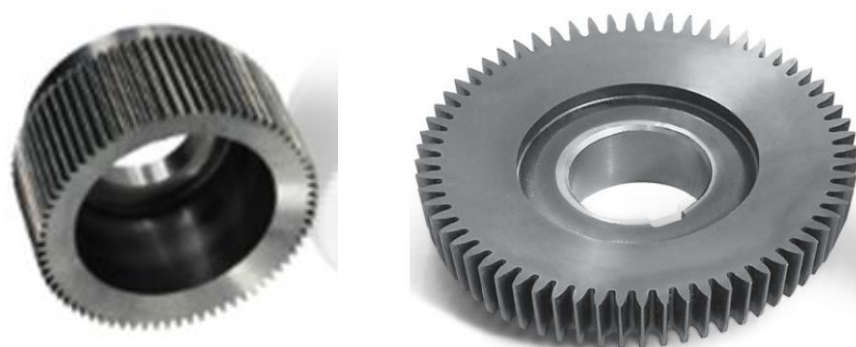


Fig.11 Spur cutters



Fig.12 Solid skiving cutters with a zero rake angle

The cutters in the Fig.12 have a zero rake angle and will therefore operate with slightly higher cutting forces and energy consumption than those analysed above. These solid tools operate at lower cutting speeds than tools with inserts with higher cutting properties.

In order to increase the efficiency of the process, non-standard tool designs are being developed, examples of which are shown in Fig.13 and Fig.14 and which their developers have defined as "Super Skiving Cutters" [20].

The purpose of these tools is to reduce the number of passes by sequentially operating the tool teeth at different levels. In both types of tool, the teeth at the first level that start cutting have the smallest height, which increases with each level until it reaches the full height of the gear tooth profile 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 level continue to cut in this gap as the tool moves in axial feed, increasing the dimensions of the gap and approaching the full height of the tooth at the exit. This should ensure a uniform distribution of the allowance between the teeth, reduce the cutting force and cut the gear in one pass.



Fig.13 Conical skiving cutters with helical teeth (a) and straight teeth (b) and spur cutter (c)[20]

#### 4.1 Consider conical skiving cutters

In these, the teeth of all levels have the same angular pitch, but because they are formed on different pitch diameters of the tool, they will have different circumferential pitches. This means that these teeth will have different modules, or on a gear cut with such a tool, teeth of different modules will be formed at different heights. As a result, the allowance removed by the higher teeth will be uneven across the width of the cavity and, in certain circumstances, the contours of the cavities may extend beyond the contour of the teeth of the tool.

The main difference of the tool in Fig.13, c is that it is a helical cutter in which teeth of different heights are tied to the outside diameter and all teeth have the same circumferential pitch. Then, as the gear is cut, the gaps and tooth profiles of the corresponding modules with the same circumferential pitch are progressively formed as the cutting depth is gradually increased. However, such a tool must be given an additional inclination in a different plane.

Common to all "Super Skiving Cutters" is that when cutting a wide gear, the teeth on all levels can participate in the cutting process simultaneously, resulting in very high cutting forces. In addition, when the higher tooth enters the cut, it contacts the workpiece on a larger diameter where the gap has not yet been cut, creating significant shock loads.

A different approach to separating the teeth of the stock removed from the gap is shown in Fig.14 [21, 22]. Here, a three-stage tool is proposed in which the teeth are divided by tooth profile height. The idea of such a tool, which consists in cutting the upper and lower parts of the cut teeth separately in two passes, was implemented in 2001 for hobs for the production of traction gears of the 8 and 10 mm module of electric locomotive drives [21, 22]. The schemes

of the column of the basic rack of the hob for the first (a) and second (b) pass are shown in Fig 15. 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.

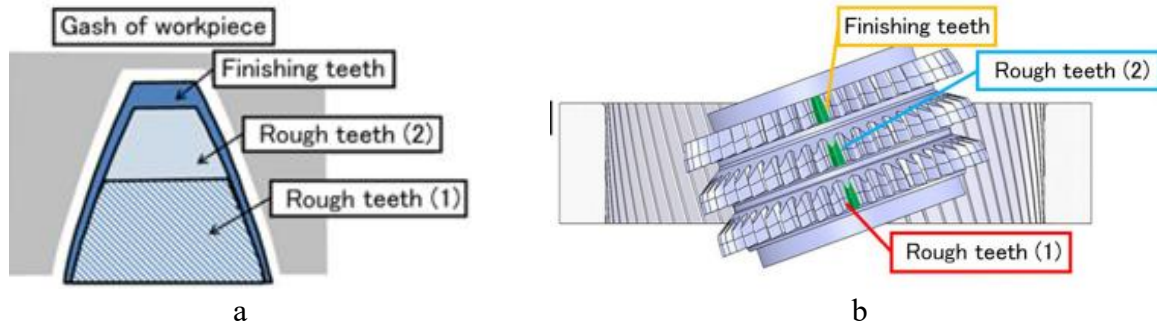


Fig. 14 Representation of the allowance distributed between the teeth of a cylindrical skiving cutter (a) and a diagram of the machining process (b) [14]

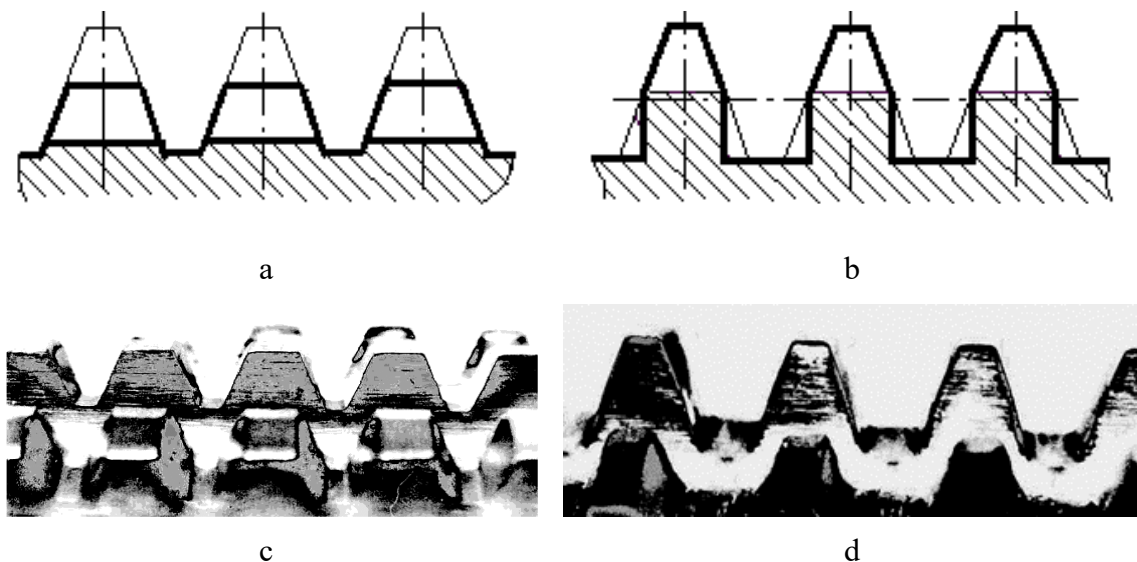


Fig. 15 Hob column design (a, b) and photos (c, d) of hobs with split base rack for first (a, c) and second (b, d) pass machining of gears of a large module [21, 22]

In general, in addition to the above-mentioned drawbacks in the design of "Super Skiving Cutters", they all have in common the high cutting forces, 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.

## Conclusions

The new interpretation of the cutting scheme in the process of machining gears using the Power Skiving method is based on the real kinematics of this process as a set of circular movements, i.e. rotation of the tool and the workpiece in planes located at an angle equal to the angle of inclination of the tool, which can have a value between  $15^\circ$  and  $40^\circ$ . This made it possible to determine the magnitude and direction of the cutting speed as the resultant vector of the circular and linear movements that ensure the gear cutting process.

The vector of the total cutting speed is important for the correct evaluation of the process, because once the skiving cutter is set up on the machine tool, it receives other values of the angles that characterise the geometry of its blades, defined as working or kinematic angles.

These angles significantly change the deformation and contact conditions on the surfaces of the cutting edges and on the blades, increasing the intensity of shearing and friction on the face and flank surfaces of the teeth. A dependence is derived to calculate the angle of the vector of the resulting cutting speed. If the initial conditions remain unchanged, this angle will remain constant for all the blades of a single tooth, so that the working angles of the skiving cutter remain unchanged along the entire length of the cutting path of the tooth.

Taking this vector into account makes it possible to

- calculate the refined cutting force on the blades and the total cutting force, which is important for predicting machining accuracy and tooth surface roughness;
- identify the causes of wear, which can be either increased shear intensity on the face or increased friction on the flank surfaces;
- on this basis, it is possible to design inserts with angles that reduce the impact of the above negative phenomena, thus increasing the tool life and reducing its cost.

The analysis of "Super Skiving Cutters" designs based on the approach described in this article showed the limits of their practical use and revealed a number of negative phenomena and disadvantages: unevenness of the allowance, possible significant displacement of the gaps relative to the coast profile of the tool teeth at different levels, increased cutting forces and shocks at the moment of cutting the teeth of each level. Studies of standard cutters showed their positive and negative characteristics and provided the basis for recommendations for their improvement.

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