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STUDY OF THE CUTTING FORCE BASED ON THE OBTAINED UNDEFORMED CHIPS DURING CUT IN WHEN MACHINING AN INTERNAL GEAR BY POWER SKIVING METHOD

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Abstract. This article explores the formation of non-deformed chips during the cut-in of an internal toothed ring using the Power Skiving method. This pivotal stage of the cutting process poses significant hazards not only in gear cutting but also in any cutting operation. The study involved modeling the process at the initial stage for various technological parameters, including cut-in depth and number of working passes. To achieve non-deformed chips, a methodology developed for worm milling was applied. The developed simulation can calculate the corresponding geometry of the cut on each rotation of the cutting tool into the workpiece. Through the utilization of a CAD / CAM environment, solid models involved in the process accurately replicate the cutting process. Based on the obtained regularities, it is possible to select optimal technological parameters and establish safe cutting modes for different gears for the respective equipment and its power parameters.

Keywords: undeformed chip, power skiving process, internal toothed ring, finite element method, simulation, cut-in.

Introduction

Machining is the basic method of manufacturing involute spline gears. In practice, methods such as hobbing, gear shaping, gear grinding, and broaching are widely used in factories due to their high efficiency and precision. Unfortunately, there are only a very limited number of manufacturing methods available for cutting the internal gear rim, let alone high-performance methods. In recent years, a new progressive method known in the literature as power skiving has gained popularity in Europe and Japan. Power skiving is a high-performance and flexible gear-cutting process that can cut internal and external, spur or helical gears, but the equipment used for cutting must have sufficient accuracy in synchronizing the spindle speeds, which are characterized by high rigidity [1]. Technological problems such as tool stability, vibration, and problems with servo synchronization, which in the past prevented the practical implement-tation of this process, have recently been overcome and it is now used not only on dedicated machines but also on 5- and 6-axis CNC machines [2]. As a result, hobbing has become increasingly common in production, and research in this area has attracted considerable interest from researchers [3].

This machining method is also effective for general profiles such as spline and herringbone surfaces, which are discussed in [4]. The continuous chip removal mechanism significantly reduces machining time. Accurate geometric modeling of the machining process is fundamental to assessing machining accuracy. Investigation of potential obstructions and hazardous contacts, as well as assessment of the working condition of the cutting edge, are important elements in further improving and optimal the machining process.

The processes associated with the cut-in and cut-out of the blade into and out of contact with the workpiece play a significant role. The magnitude and direction of the cutting force applied to the material are important characteristics of this process. They determine the operating conditions of the machine tool,

tool, fixture, workpiece accuracy, etc. Let's take a closer look at the operating conditions of the tool and the geometric characteristics of the undeformed chips produced at this stage. In this article, we will consider the process of cut-in a blade into the material to be machined.

Fig. 1. General view of an internal gear machined by power skiving [5]

Review of primary sources

Unfortunately, studies of the processes that take place at the moment the tool cuting-in the workpiece are very rare in the literature. Authors mainly study the power skiving process using different methods: analytical, graphical, Boolean, and finite element methods to determine different patterns [6–8].

These works show that analytical methods have excellent characteristics when studying the accuracy and instantaneousness of the contact. The analytical method is also suitable for machining helical surfaces. However, in general profile machining tasks, potential singular point conditions, and interference have limited the use of analytical methods. By representing a continuous motion through a series of successive positions [9, 10], numerical methods avoid the establishment of analytical envelope equations. This method improves robustness to interference and undercutting [11] and increases the generality for processing universal profiles [12]. The main focus of these studies is on the discrimination of the profile to be processed, but the instantaneous generation conditions are hardly discussed.

However, the geometric and kinematic complexity of this process makes it difficult to model and simulate analytically. Spath and Hühsam [13], who studied the design with power tools, used a simplified calculation of the resulting force. Tachikawa et al. [14] correlated the harmonic components of the normalized cutting forces with the cutting speed and selected speeds that avoided structural vibration. To cope with the complexity of the geometry and kinematics, Klocke et al. [15] used a plane section method to numerically approximate the engagement of the cutter with the workpiece at each step. Other more accurate approaches, such as solid-state modeling by Tapoglou [16] and 3D finite element modeling by Schulze et al. [17], provide greater accuracy in the study of chip formation but can be computationally intensive.

In addition, even though this work has been carried out for specific engineering tasks, a general model of two-parameter machining, which includes the full geometric and kinematic parameters of common gear-cutting methods, was still lacking.

As the literature review shows, there is still a need for research into a general mathematical model of the processes that take place during workpiece cutting. Taking into account the excellent characteristics such as accuracy and instantaneous study of analytical methods, as well as the stability and generality of numerical methods, a 3D model of an undeformed chip was developed in this study. All its geometric parameters were determined and, based on these data; the forces generated at the moment of plunge during the machining of internal involute spur gears were analyzed.

Aim of the study

The purpose of this study is to model the process of the cut-in tool the workpiece during the cutting of an internal gear rim for different technological parameters, namely the depth of cut and the number of work passes. This important stage of the cutting process is one of the most dangerous not only in gear turning, but in any cutting operation. It is known that cut-in is responsible for the largest number of tool failures [18]. During the cutting process, the cut-in and tool exit phase is accompanied by dynamic oscillations, impacts and sharp alternating stresses.

Research results

To construct an undeformed chip, we use a methodology developed for hobbing [19]. The principle of its application is to consider the cutting process as discrete positions of the tooth contour at each instant. Each such position of the cutter is determined taking into account the angle of rotation and its passage in the axial direction per unit of time, and the corresponding index “*i*” is assigned (Fig. 4). It is therefore necessary to display the contours of the tool teeth, for example, for some n revolutions in relation to the angle of rotation at $(i–1)\varphi$ and then in the same positions but for $n+1$ revolutions and taking into account the axial feed rate $(i–1)s_o$. By comparing these contours, it is possible to obtain a representation of the instantaneous section of the cut. This is the contour of the cut made by a given cutter tooth at a given time in its working position.

By adding up all the sections of the undeformed chip obtained for each discrete tool position, the dynamics of the chip geometry can be followed and a 3D model can be obtained by applying a kinematic operation in the software environment. Although finite element modeling gives results close to those obtained during the experiment, it requires high computational power and good knowledge to adjust the modeling.

More computationally efficient are the results obtained from analytical calculations. It is necessary to describe the movement of 2 parts (workpiece and cutter) analytically, i. e. to determine their positions at each instant. By superimposing the respective profiles of the gear and the cutter tooth concerning each other, it is possible to obtain a cross-section of the chip formed at the position in question. When the geometric cut-in of the tool into the workpiece is calculated, it is reduced to a set of two-dimensional superpositions of the linear planes of their profiles. The results of modeling gear cutting using this method have been successfully confirmed in the past [20]. By evaluating the simulation results, the progress of the cutting process can be determined. It is also possible to generate a digital design of the final geometry of the gears [21] and chips [22].

To perform the plunge calculation, it is necessary to describe the tool and the workpiece parametrically. We will use the method already described [23] for the power skiving process but during plunge cutting. And while in [23] the steady state cutting mode was considered for different technological cutting parameters, the cut-in phase is a key and extremely important phase in the considered hobbing process and can influence the allocation of the number of passes and change the recommended technological values.

The gear-turning process is analyzed in terms of maximum chip thickness and, on this basis, recommendations for process design are proposed. The simulation developed is capable of calculating the appropriate cutting geometry for each revolution of the tool cut in the workpiece. Chip thickness and chip area are calculated and the results are entered into a table. Using the designed cutter profile and transition surface, the depth of cut-in of the tool into the workpiece can be calculated for discrete-time and space intervals. Finally, the developed simulation was tested on a gear with an internal gear rim.

Consider the case of cutting a gear with the following initial data:

– involute spur gear;
– module 2.5 mm;
– number of teeth: gear 33, cutter 24;
– axial feed 0.5 mm/rev;
– cutting speed 190 m/min;
– angle of inclination of cutter teeth and angle of intersection of axes 25^0;
– number of passes: four.
– material of the cutting plates – hard titanium-tantalum alloy;
– rim height 30 mm;
– the coefficient of friction on the face for a given speed is 0.63.

To study the process of cutting teeth on a gear, consider the process for four passes. Note that the first passes will have a shorter trajectory, so we will start with a greater depth and then reduce it for each subsequent pass.

Let's spread the total depth over the passes: 1.5 mm; 1.5 mm; 1.375 mm and 1.25 mm for the four passes respectively.

To obtain the correct chip cut and reproduce the cut-in process, it is necessary to calculate analytically the position of the cutter tooth and the resulting depression on the gear obtained on the previous revolution. Such calculations have been carried out using the system of equations for the intersection of an oval (cutter) and a circle (gear), which has been compiled for the practical example considered and confirmed by 3D modeling (Fig. 2).

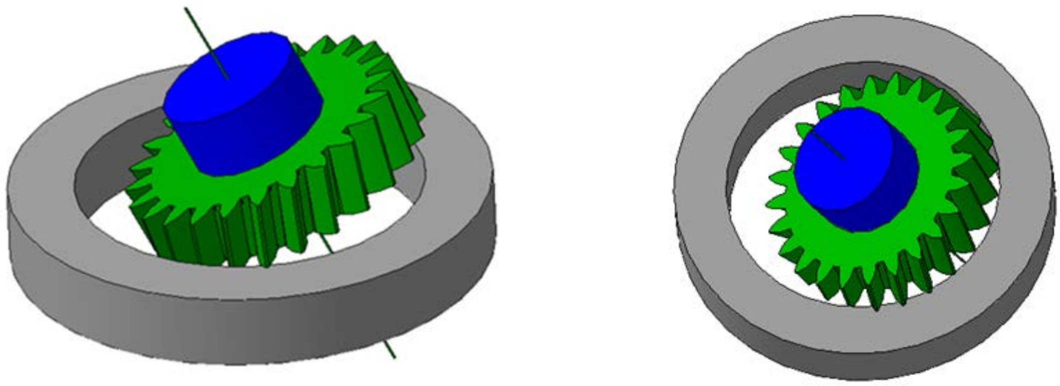


Fig. 2. 3D modeling of the power skiving process

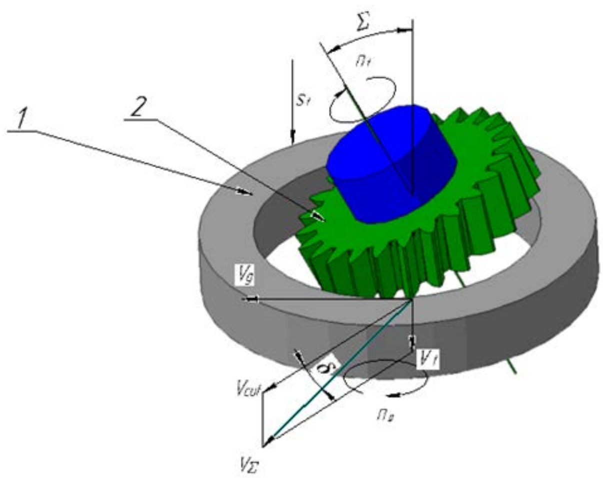
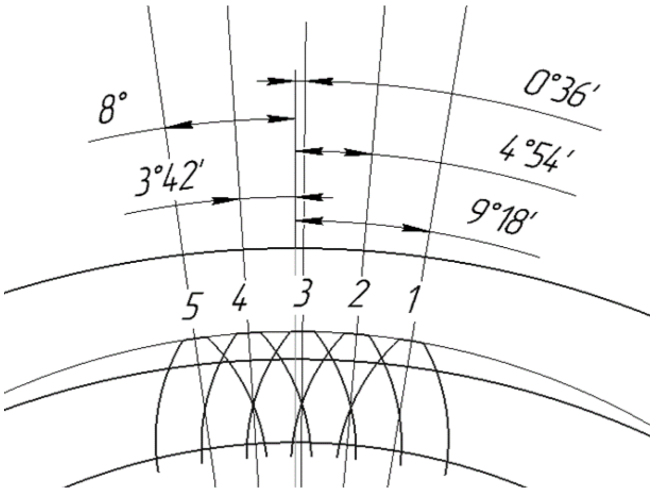


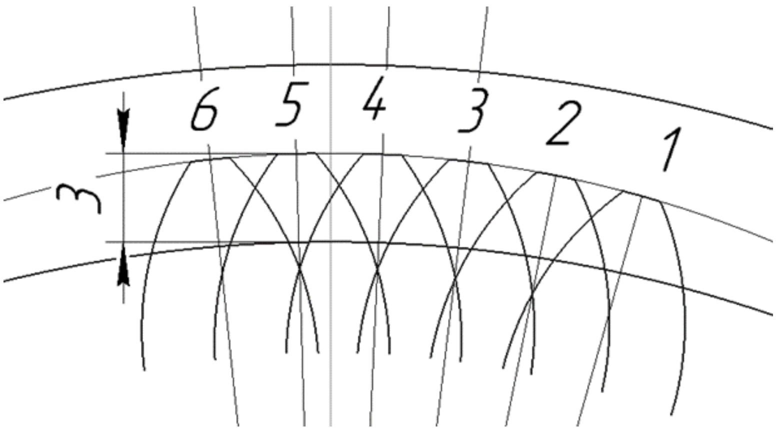
Fig. 3. Kinematic diagram of the tool / workpiece arrangement for the power skiving method

By using the CAD environment, the solid models involved in the process reproduce the cutting process with the greatest possible accuracy. For each of these positions, the exact position of the cutter and the intermediate position of the workpiece at that time have been determined. The simulation also allows the cutting process to be modeled and improves process insight to understand the cutting process.

The model's approach of using sequential profiles to describe tool movement in three dimensions allows better control over the accuracy of the solid created.



a



b

Fig. 4. Projections of the cutter tooth onto the workpiece during plunge cutting at different revolutions: a – for the first pass (depth 1.5 mm); b – for the second pass (depth 3.0 mm)

To simulate the cutting process, all movements that occur during the process are considered at a given time and fixed at a given position. Thus, tool 2 rotates as if on its own axis at a given speed V_{cut}. The tool is tilted by a certain angle Σ (Fig. 3) and it also moves along the axis of rotation of the workpiece – V_t.

To adequately reproduce the power skiving process, the simulation model reflected the tool movements:

– n_t is the frequency of rotation of the tool around its axis;

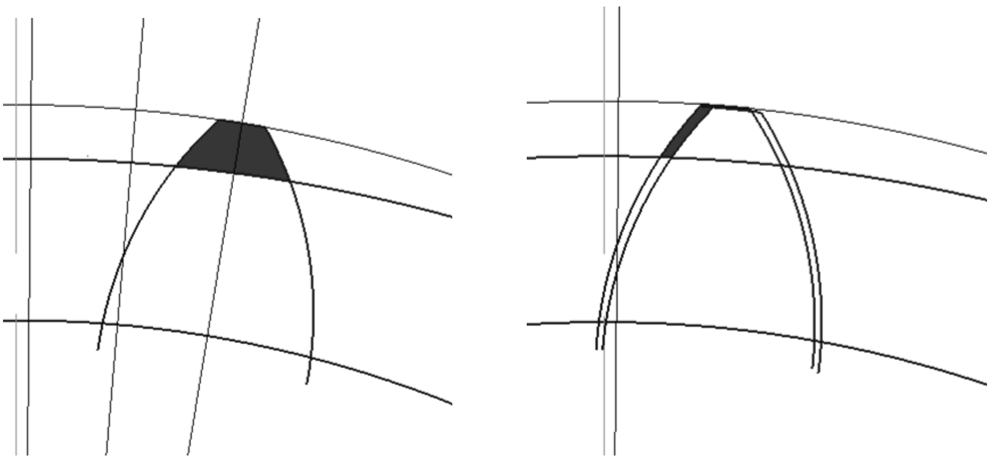
– n_g is the frequency of rotation of the gear workpiece about its axis;

– Σ is the angle of inclination of the tool relative to the workpiece. In production, this angle ranges from 15^0 to 35^0. The greater the angle of inclination, the lower the angular speed required for the cutting process, but since the angle cannot be increased from a technological point of view, especially for internal cutting, we will take its value as 25^0 in our case;

s_t – tool feed along the axis of rotation of the gear part.

Fig. 3 shows a 3D model of the tool and workpiece arrangement for the power skiving process. The simulation model represents each discrete position of the cutter and gear, and by superimposing the transitional cut surface obtained at the *i-th* revolution and the cutter position at the $i+1$ position, a cut profile can be obtained. The first step in modeling is to create and position the transition surface profile. For ease of visualization, let's project the view onto a plane.

Taking into account that the center distance between the gear and the cutter will change for each pass, the engagement zone between the tool and the gear workpiece will be distributed depending on the pass. Consider the case when the entire cutting process will take place in 4 passes. On the first pass, when the depth of overlap is 1.5 mm (Fig. 4, *a*), the meshing zone of the tool with the gear workpiece will be divided into 5 consecutive angular positions, marked 1, 2, 3, 4, 5. The first revolution of the cutter at which cutting occurs will correspond to position 1 (the position is offset to the right of the vertical by 9º18′), at the second revolution – position 2 (4º54′), at the third revolution (position 3) the angle is 0º36′. At the fourth position 4, the angle will be offset in the other direction and will be equal to 3º42′ (analytical calculations determined the angles). The fifth position will also be located after the vertical, and the angle to the left will be 8º, which corresponds to the exit of the tool from the cutting zone (in this position there will be almost no cutting). This means that 5.5 tool revolutions are required for steady-state cutting. For the next pass with a depth of overlap of 3 mm, there will be 6 such positions since the overlap zone in this case will be larger (Fig. 4, *b*). For this depth, we designate a new position 1, which will correspond to the plunge on the first revolution, and then all other positions will correspond similarly to the previous pass 2→1, 3→2...



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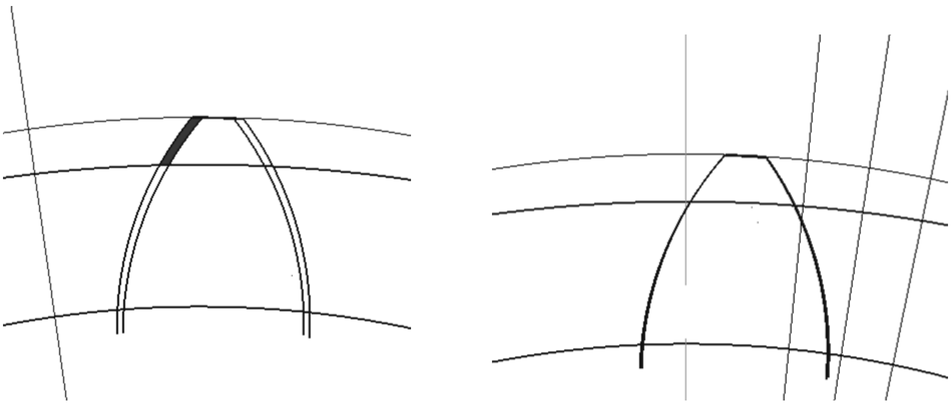

c d

Fig. 5. Chip sections formed during the cutting process from the first revolution (a) to the fourth revolution (d)

In this way, all the basic cutter positions are calculated for each pass and each depth.

As the workpiece is still a solid body on the first pass and the first revolution of the cutter, the first cut is solid and corresponds to the overlap of the cutter tooth and the workpiece (Fig. 5, *a*). On the second revolution, the cutter profile will be in position 2 and the cut obtained after the first revolution must be set in a position offset by the feed multiplied by the gear ratio. It is necessary to combine the profile of the cutter and the cut obtained after the first pass – we obtain the second cut (the shaded area) (Fig. 5, *b*). Carry out the same operation for the next position. We will obtain an ensemble of slices on each revolution (Fig. 5, *c*). With this depth of overlap between the tool and the workpiece, the cutting process will go into a steady state on the sixth revolution. We are not interested in this in this article, as it has already been considered in [21]. Let's carry out the same procedure for the next overlap depths of 4.375 mm and 5.625 mm. As can be seen in Fig. 4, the number of cut-in revolutions and, consequently, the positions increase to establish a stationary cutting mode at a greater overlap depth. In particular, at a full depth of cut of 5.625 mm, 7.1 such cut-in revolutions into the workpiece are required to reach the steady state of the tool.

Using the same methodology, we can study at other strategies for cutting the flank, namely at a feed rate of 0.75 mm/rev.

Research results

The simulation was carried out for the cutting of an internal gear (see above for input data) and the results (for the first passes) are shown graphically (Fig. 5). To understand the operation of the cutter better, its blades can be divided into parts: lead, upper and trail. This will involve a lot of calculations, but it will give an understanding of which blades work in a more intensive mode, and how to take into account the work of each cutting part of the cutter tooth. Based on the results of the study, it is possible to select the optimal strategy for cutting the gear ring, according to the capabilities of the equipment. By setting the cutting force, which depends directly on the area of undeformed chips (using the Kinzle formula), the required number of passes and tool feed can be selected. Analyzing the cut of each strategy (depth of cut for each tool pass) will allow you to see the work properly and draw conclusions for improving the working mode. The influence of the perception of the type of change in chip thickness and chip area depends on the position of the cutter tooth, these results are shown in Table 1–8.

Table 1

The cross section's area of undeformed chips on the first pass at a depth of 1.5 mm

Angular position of the cutter tooth, º		9.3	4.9	0.6	–3.6
Position		1	2	3	4
Area of cross section, mm^2	Trail blade	0.000	0.335	0.331	0.000
	Upp blade	2.260	0.056	0.020	0.000
	Lead blade	0.000	0.000	0.000	0.013

Table 2

Average cross-sectional thickness of undeformed chips on the first pass at a depth of 1.5 mm

Angular position of the cutter tooth, º		9.3	4.9	0.6	–3.6
Position		1	2	3	4
Average cross-sectional thickness, mm	Trail blade	0.000	0.230	0.220	0.000
	Upp blade	0.861	0.055	0.020	0.000
	Lead blade	0.000	0.000	0.000	0.014

Table 3

The cross section's area of undeformed chips on the second pass at a depth of 3 mm

Angular position of the cutter tooth, º		15.7	11.3	6.9	2.6	–1.7
Position		1	2	3	4	5
Area of cross section, mm^2	Trail blade	0.0	0.295	0.268	0.260	0.006
	Upp blade	5.740	0.133	0.088	0.042	0.004
	Lead blade	0.000	0.000	0.000	0.000	0.000

Table 4

Average cross-sectional thickness of undeformed chips on the second pass at a depth of 3 mm

Angular position of the cutter tooth, º		15.7	11.3	6.9	2.6	–1.7
Position		1	2	3	4	5
Average cross-sectional thickness, mm	Trail blade	0.000	0.215	0.190	0.180	0.000
	Upp blade	1.780	0.115	0.076	0.040	0.000
	Lead blade	0.000	0.000	0.000	0.000	0.000

Table 5

The cross section's area of undeformed chips on the third pass at a depth of 4,375 mm

Angular position of the cutter tooth, º		20.7	16.1	11.7	7.3	3	–1.3
Position		1	2	3	4	5	6
Area of cross section, mm^2	Trail blade	0.000	0.374	0.305	0.259	0.239	0.133
	Upp blade	8.023	0.225	0.159	0.105	0.054	0.009
	Lead blade	0.000	0.000	0.000	0.000	0.000	0.000

Table 6

Average cross-sectional thickness of undeformed chips on the third pass at a depth of 4,375 mm

Angular position of the cutter tooth, º		20.7	16.1	11.7	7.3	3	–1.3
Position		1	2	3	4	5	6
Average cross-sectional thickness, mm	Trail blade	0.000	0.222	0.174	0.144	0.123	0.041
	Upp blade	2.550	0.184	0.136	0.094	0.051	0.010
	Lead blade	0.000	0.000	0.000	0.000	0.000	0.000

Table 7

The cross section's area of undeformed chips on the fourth pass at a depth of 5.675 mm

Angular position of the cutter tooth, º		24.7	20.1	15.6	11.2	6.8	2.5	–1.8
Position		1	2	3	4	5	6	7
Area of cross section, mm^2	Trail blade	0.000	0.383	0.216	0.110	0.137	0.122	0.014
	Upp blade	8.770	0.318	0.242	0.175	0.114	0.056	0.004
	Lead blade	0.000	0.000	0.107	0.193	0.051	0.004	0.000

Table 8

Average cross-sectional thickness of undeformed chips on the fourth pass at a depth of 5,675 mm

Angular position of the cutter tooth, º		24.7	20.1	15.6	11.2	6.8	2.5	–1.8
Position		1	2	3	4	5	6	7
Average cross-sectional thickness, mm	Trail blade	0.000	0.318	0.174	0.084	0.100	0.070	0.008
	Upp blade	2.000	0.249	0.200	0.148	0.100	0.052	0.004
	Lead blade	0.000	0.000	0.052	0.084	0.023	0.008	0.000

As can be seen from Table 1–8, regardless of the pass selected, the maximum cutting area and undeformed chip thickness occur during the first revolution. This characteristic also applies to any feed rate, as the tool tooth is immediately cut into by a significant amount (see table). This is therefore the most dangerous stage of gear cutting. This cut is made at the top of the blade and the results of the first revolution should be taken into account when selecting the appropriate cutting mode (number of passes, depth of cut, feed rate, etc.). For the selected depths of cut, it can be seen that the cutting area on the last pass and the first revolution is the maximum value (Table 1–2). On the second and subsequent revolutions, the characteristics are much lower, and on the last revolution of the cut-in stage, they are even close to 0. This is also dangerous. A small chip thickness leads to a high intensity of forces, temperatures, and stresses. After the 7th revolution, the cutting process goes into a steady state. If the difference in depth of cut between the penultimate (third) and the last (fourth) revolution of the cutting tool is smaller (up to 0.5 mm, in the form of a finishing pass), the areas will be smaller. Such assumptions can be made in subsequent studies to verify their validity.

The chip geometry for the different strategies and passes remains constant and is typical for all revolutions (Fig. 5). The only difference is the chip area and thickness. The cutting process on the first revolution starts in all cases with the upper blade (Fig. 5, *a*), then on the next revolution, the cup cutter works with all blades (Fig. 5, *b*–*d*), only on the last revolution of the cut-in stage the cutting is performed with the lead blade (Fig. 5, *e*).

Tables 1–8 show that for the upper blade, the area of undeformed chips gradually decreases (from the 1st to the 7th revolution) and is absent at the last revolution. Conversely, the lead blade of the cutter tooth does not cut at the first revolution (Table 1–8), and then the load on it gradually increases, where it decreases again after passing the center of the path. At the last revolution of the cut-in stage, the tool is the only one working, although the area is smaller than in the previous revolution.

Therefore, when analyzing the cut-in stage, the number of passes does not have a significant effect on the cutting area, but only during stationary cutting. The final passes for each strategy determine the maximum forces experienced by the cutting tool, and it is on these that you should focus. It can be concluded that the depth of cut for the first passes can be set to a higher value, while the depth of cut for the last passes should be reduced.

For a given cutting area, the cutting forces can be calculated and the depth of cut selected so that the technical capabilities of the machine (permissible forces and critical power) allow safe gear turning. As expected, the chip areas and thicknesses increase with each subsequent pass and are very high for these depths of cut and feed rates. The tool and equipment are subjected to high loads and temperatures, which hurt tool performance. Such conditions are not suitable for the cut-in phase. While it is possible to cut at a feed rate of 0.5 mm/rev in 4 passes in stationary cutting mode [26], such operating conditions are extremely dangerous for cut-in.

In the case under consideration, it can be seen that the total cutting area is generally greater than 5 mm^2, which is unacceptable for the tool. In this case, it is essential to reduce the depth of the cut, especially in the final passes (increase the number of passes and reduce the feed rate). Depending on the characteristics of the equipment and its performance parameters, it is possible to select the optimum process values and set the final cutting performance.

Conclusions

There are different strategies and approaches to controlling the cutting process in gear turning. Possible options: with the chosen number of passes, select the appropriate feed rate that will allow you to stay within the limits of the machine's strength and power. You can change the number of passes for a given axial feed and, in any case, you must also take into account the cutting speed that will allow you to obtain an acceptable tooth surface quality and accuracy. As can be seen from the initial data, this task is a multifactorial study to find the optimum selection of technological parameters, the main purpose of which is machining time.

Such studies can also be carried out for different axial tool feeds, at different angles of inclination, for cutting gears with different modules, and for the number of teeth of the tool and the gear.

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