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INFLUENCE OF AXIAL TOOL FEED ON UNDEFORMED CHIP GEOMETRIES IN POWER SKIVING GEAR CUTTING

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Abstract. The purpose of this article was to formulate recommendations for developing strategies for multi-tool cutting of gear wheels that ensure a productive and reliable process for ensuring the accuracy and quality of machined surfaces. The determination of the effective axial feed rate to achieve maximum productivity has not yet been fully explored. The objective of this article is to ascertain and examine the impact of axial feed on the chip formation process during the cutting of the gear rim. The objective is to achieve optimal cutting conditions in each cut, thereby increasing tool life and process reliability, while concomitantly reducing processing time. The challenge of power skiving technology is to determine the effective cutting mode parameters, which include axial feed and cutting speed, depth of cut, and number of passes, as well as tool angle and cutting edge geometry of the skiving tooth. It is recommended that the optimal cutting parameters for the corresponding gear be determined based on the obtained results.

Keywords: power skiving, axial feed, undeformed chip, simulation, gear cutting process, skiver tool.

Introduction

In the last decade, the gear skiving process using the Power Skiving method has been increasingly encountered among gear manufacturers, demonstrating significant potential for implementation in leading enterprises. Although the principle of the process was described in the early 20th century and patented by Wilhelm von Pittler in 1912 [1], gear cutting was not used on an industrial scale for a long time. It was the introduction of high-precision CNC machines and the ability of modern computer technology to calculate complex tool geometries that paved the way for its gradual introduction into the technological chains of gear manufacturing machines. Since the beginning of the 21st century, power skiving has been increasingly used in industry. This method has significant advantages in terms of manufacturing performance compared to the traditional gear cutting process. Gear shaping has very long production times due to intermittent movements. Both broaching and hobbing require expensive tools and specialised equipment. While the former can be used to cut the internal gear rim, hobbing with worm cutters is only used to produce external gears. A particular problem is the production of external or internal gears with interfering contours.

An alternative to these methods is power skiving, which is characterised by continuous rolling at very high speeds (in most cases up to 200 m/min) and therefore allows minimum production times. However, the potential of this method has not yet been fully exploited, and it is currently the subject of various studies by different researchers: improving the tool structure, finding the optimum cutting modes, increasing tool life and coating, and selecting the necessary equipment requirements. One of the main challenges facing researchers is the complex and rapidly changing system of velocity and force vectors. In addition, the high speeds involved in skiving create a number of dynamic effects during tool operation, which induce vibrations in the machine's structural elements in critical areas. In order to avoid severe wear or even complete failure of expensive tools, multi-pass machining strategies and feed rate determination have been used.

Elon Musk (Founder of Tesla, SpaceX):
"Creating the factory of the future is a hundred times harder than designing a new car. Mechanical engineering is the art of optimizing systems, not just building products."
(About automation and scalable production)

The great potential of finding an efficient axial feed for maximum productivity has not yet been fully exploited. The purpose of this article is to determine and analyse the effect of axial feed on the chip formation process during gear cutting. Based on the results obtained, the optimum values of this process variable are recommended for a given gear.

Gear pre-turning mainly involves cutting processes with geometrically defined cutting edges and forming technologies. The aim of the operation is to produce the basic geometry of the gear, usually an involute, in a productive and highly accurate manner. All running parts, i.e. cylindrical gears that are subjected to sliding friction stresses during operation, are heat treated in later stages of the process chain to increase the material hardness in the gear contact area and thus its lateral load capacity. Due to the geometric distortions resulting from this thermo-chemical treatment of the material, an additional fine machining of the gear is usually required.

The main arguments in favor of two-stage gear geometry production are, on the one hand, the ever-increasing demands on modern gearboxes in terms of power density, smoothness and service life. On the other hand, manufacturing processes must be cost-effective and highly productive. The processes used must therefore be able to produce gears that meet the requirements in a short time and at low cost - for example, in terms of tools or auxiliary materials.

Review of primary sources

Over the past decade, a significant number of experimental studies have been carried out and modelled on the Power Skiving gear cutting process. In order to mathematically describe any phenomenon associated with a particular process, an appropriate kinematic scheme is first required. An analysis of the primary sources shows that many well-known studies of this gear cutting process incorrectly estimate its kinematics. For example, in [2] the cutting speed is represented by a vector coinciding in direction with the axial feed (Fig. 1) and is defined as the vectorial sum of the linear rotational speeds of the workpiece and the tool.

One of the methods for modelling 3D chip is the finite element method used in [3, 4]. The authors reproduce the kinematics of the cutting process using commercial CAD software, model an undeformed chip and calculate the cutting forces from the data obtained. However, they consider a rectilinear cutter profile and incorrectly reproduce the process kinematics, leading to inadequate results.

A significant drawback of [3, 5-9] is the inaccurate reproduction of the process kinematics. This paper presents an approach to modelling the power skiving process to predict the undeformed geometry of the chip and the morphology of the manufactured gear using a computer aided design (CAD) system. The chip thickness can be calculated from the simulation analysis. However, the cutting motion is formed by the combination of two motions - the axial feed rate and the speed of the main motion, which is applied to the tool rather than the workpiece, as is usual in this work. As a result, the resulting velocity vector is directed at a different angle relative to the reference surfaces and axes. This is important for the correct determination of cutting forces, friction and geometric parameters of the chip.

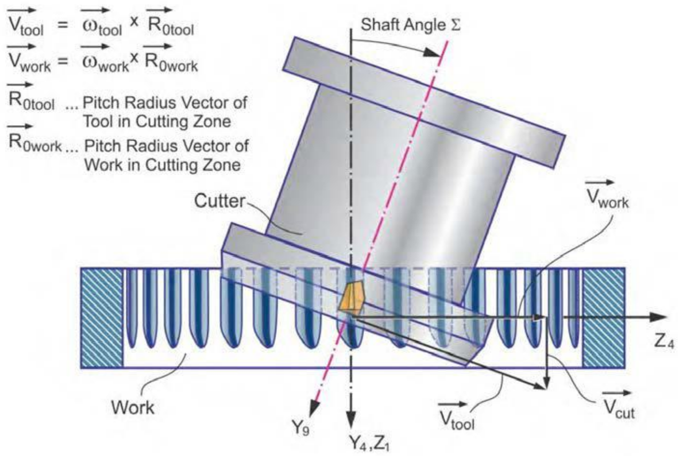

Fig. 1 Kinematic diagram for calculating the cutting speed [2]

The paper [4] describes a new virtual model for predicting raw chip geometry and cutting forces in power skiving, a high-speed, versatile gear cutting process. In the kinematic model of this thesis, the cutting speed is represented along the discretised cutting edges and based on this data, the optimal rake and clearance angles are calculated. Incorrect interpretation of the process kinematics leads to incorrect chip formation and, as a result, to an approximate prediction of the cutting force.

In [3, 4, 10-12] there is no systematic mathematical model for the design and analysis of gear cutting tools. The shape and dimensions of the transition surface formed in the valley between the teeth by the tool in the previous axial position along the feed direction are not taken into account. Such an incorrect interpretation of kinematics, which is accepted in the above-mentioned primary sources, leads to an incorrect assessment of the cutting force, its effect on the process, the determination of the actual geometric parameters of the cutting tool, as well as the friction forces on its surfaces.

A review of primary sources shows that power skiving is not as well studied as most traditional machining processes such as hobbing, broaching and forming, which provides additional opportunities for further implementation and opens up new horizons for this method. Solving these problems requires a fundamental understanding of the kinematics and cutting forces that occur during machining. However, due to the complexity of the kinematics and mutual displacement geometry, analytical methods for studying cutting forces are extremely difficult to implement.

Research Results

The kinematics of the power skiving process is similar to that of helical gear cutting, where the workpiece and tool rotate continuously and synchronously relative to each other. A characteristic feature of this process is the angle between the tool and workpiece axes, which is usually φ=20-30º. The correct choice of this parameter affects almost all important variables in tool and process behavior and, not least, determines the productivity of a particular application. From a kinematic perspective, introducing the inclination angle of the rotating tool's transverse axis leads to the appearance of a cutting speed vector V_{Σ}, which is the resultant vector of two velocities V_{cut} and V_f (Fig. 2). As with a disc-type gear shaping cutter, the tooth shape of the skiver tool is involute. The tool or workpiece is fed along the axis.

During the power skiving process, the main cutting motion is the rotation of the cutter combined with its movement along the workpiece axis due to the inclination of its axis (for a spur gear). The auxiliary movements are the axial feed of the tool and the rotary feed of the workpiece. The vectors of these movements are given in Fig. 2: V_{cut} - speed of rotation of the cup-shaped cutter; V_f - speed of movement of the tool in the axial feed, which coincides with the speed of lowering of the teeth along the gear axis due to the axis crossing; V_g - speed of rotation of the gear; V_{Σ} - speed of the resulting cutting movement.

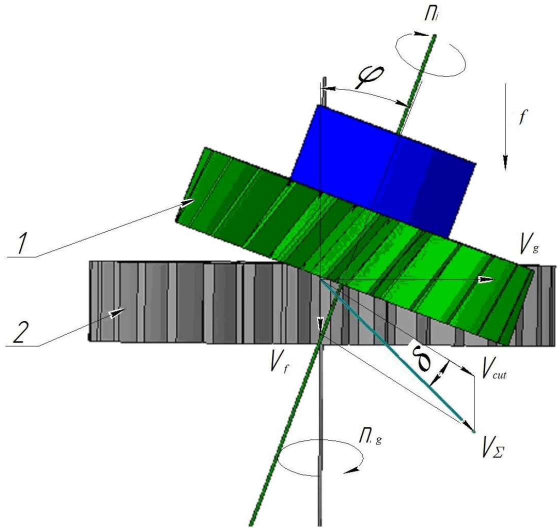

Fig. 2. Kinematic diagram of the Power Skiving method

Gear milling can be used on any machine tool that has a rotary axis and rotating workpiece and tool axes. In addition, the two rotary axes must be coupled on the control side. In principle, these requirements apply to many universal machines, such as turn-milling centers. However, specialised machines are also available for this process (Fig. 3).

Fig. 3. JCS30 CNC Power Skiving [13]

Feed strategies

Unlike other gear cutting processes with a fixed cutting edge, power skiving is characterised by highly variable cutting conditions during engagement. For example, it is well known that the clearance angle is around 0 degrees at the entry of the cutting edge, decreases significantly as cutting progresses, and becomes strongly negative at the exit of the cutting edge [14]. This significantly impairs chip evacuation, causing chips to weld and jam under the highly inclined leading face, which can lead to tool breakage at higher chip thicknesses. The process characteristics described above mean that the current state of the art in gear cutting does not allow the maximum possible full depth of cut ap, which for gears corresponds to the tooth height h of the workpiece, to be used to produce a gear in a single pass. Instead, multi-cutting strategies are always used today. Depending on the geometric characteristics of the gear, its modulus, tooth height and meshing conditions, which are very different for the outer and inner rims, between 3 and 20 passes, are made. The number and depth of cuts for each pass are usually determined by experience or previous trials. In most cases, the same tool is used for all preliminary and final cuts.

Mathematical approach

The most important prerequisite for modelling the kinematic and geometric relationships between workpiece and tool is the representation of the gear on which the hobbing process is based.

Wear analysis at the cutting edge shows similar curves when tested at feed rates in the average range of 0.15 mm/rev to 0.75 mm/rev. At very low feed rates of f = 0.05 mm/rev and at very high feed rates of f = 0.85 mm/rev, the cutting edge is severely worn and broken out [14]. The fact that these two failures have different causes can be seen from the wear patterns. At very low feed rates, the average chip thickness h_m is significantly less than the cutting edge radius. This results in very unfavourable engagement conditions, especially due to the permanent negative lead angles at the cutting edge radius. The material is compressed and crushed and the chips are not cut cleanly. These effects are more pronounced when machining with a rising cutting edge, as in this case. The cutting edge is subjected to a high abrasive load, which increases the radius of the cutting edge. This increases the effect described above. In addition, as the feed rate decreases, the number of impacts on the cutting edge increases at a constant feed rate [14]. When a certain maximum critical feed rate is exceeded, the cutting edge wears out due to severe flank wear and chipping of the cutting edge. At high feed rates, the required minimum rake angles are no longer achieved - the side face is scored and, in the case of carbide, the cutting edge inevitably breaks out. The dependence of the effective rake angle at the entry of the cutting edge on the feed rate is a significant limitation on cutting performance, but can be influenced by carefully selected setup parameters.

Structuring the problem

The problem was formulated to provide guidelines for the design of multi-cutting strategies that ensure a productive and safe process. This requires a thorough understanding of the process based on an accurate and meaningful computational model.

This paper focuses on the fact that efficient feed rates are always required during hobbing to achieve the required depth of cut. This means that for up to 95% of all cuts, the set values are not technologically determined, tied to design values, but can be changed within certain limits. For example, according to the state of the art, the centre distance in each pass will naturally vary to achieve the desired uneven feed depth a_p[14]. However, since the formation of a suitable profile in the preliminary cuts is not essential for the geometry of the final gear, other variables on the gear can also be varied, such as the centre line angle, the face offset or the meshing angle. The aim is to achieve optimum cutting conditions for each cut, thereby increasing tool life and process reliability and reducing machining time [15]. The evaluation parameters obtained with the mathematical model were used as a basis. On the basis of these studies, improved - i.e. more productive and safer - strategies for selecting the required feed are being developed.

Power skiving technology faces the problem of setting effective parameters for the cutting modes, which include axial feed and cutting speed, depth of cut and number of passes, as well as tool angle and geometry of the cutting edge of the skiving tooth. In order to increase the productivity of gear production using this method, and to avoid a constant experimental and individual approach in each case, when developing a technological process it is necessary to coordinate in detail the combination of various factors: cutting speed, feed, depth and number of passes, taking into account the capabilities of the machine tool in terms of power and rigidity, in particular the tool spindle, especially when cutting planetary gears.

Let's consider the relationship between the geometric parameters of the undeformed chips for each position of the cutter tooth in discrete positions of its rotation during a cut.

The main regularities of the cut layers, the distribution of the oversized between the blades of the cutting teeth of the tool, and their participation in the formation of the tooth surface of the wheel can be analysed using the example of the cutting of a cylindrical gear with external and internal rims.

Research results

To solve this problem, we will use the graph analysis method developed in [15]. This original approach has been used to model the parameters of chip cuts in worm gear milling. Unlike existing chip modelling methods [3], which are based on the mathematical description of splines, the proposed and tested method uses a different approach. It makes it possible to describe the forming motion of the tool of the working surface by a set of its successive instantaneous cross-sections by other characteristic surfaces [16].

The essence of this method is that in each position of the tool tooth, the movement traces are reproduced in its current position, as well as in the positions occupied by this tooth on the cutting path in axial feed, the corresponding angular position of this tooth and the corresponding angular position of the surface traces that partially formed the depression in the previous cutting cycle. The continuous cutting and forming process is represented by a sequence of discrete movements that take into account the angular and linear displacements of the tool and the workpiece, according to the kinematics of a particular method. They are easily described mathematically. In each position of a tool tooth, the traces of the movements in its current position and in the positions occupied by this tooth at the previous axial and circular feeds are reproduced [17].

Let's consider the case of cutting a spur gear with the following parameters:

Involute spur gears with external and internal teeth;

Module 2.5 mm;

Number of teeth: gear 33, cutter 24;

Axial feed 0.3-0.75 mm/rev;

Cutting speed 190 m/min;

Cutter material - hard titanium-tantalum alloy;

The angle of rake and the intersection of the cutter teeth are 20 degrees.

Crown height 22 mm;

Coefficient of friction on the face for the given speed 0.63.

The essence of the developed modelling method lies in the fact that, based on the analysis of a given gear cutting process and considering all its kinematic features, the instantaneous cross-sections of the cuts are reproduced at discrete angular positions of the gear workpiece and the cutting tool.

The obtained cross-sectional parameters of the chip layers formed during the cutting process are used as a basis for modelling and calculating the cutting forces, friction, work required to remove the oversize, tool heating intensity, heat flows generated during cutting, temperature and tool wear, dynamic processes and modelling vibrations. Complete information about the dimensions (width, length, chip thickness, chip area) and shape of the cut layers, their size in different areas (lead, trail and upper part of blades) of the tooth at each moment of cutting, as well as the determination of the regularity of their continuous cyclical change per revolution of the cutting tool, serve as a basis for a comprehensive reproduction and description of various interrelated and interdependent deformation and contact processes that occur during the process of cutting a gear ring.

Based on the developed graph analysis methodology, the results of modelling undeformed chips for the inner gear ring (Figures 4–5) and for the outer gear ring (Figures 6–7) were obtained. The number of discrete axial tool feeds is 4, varying from 0.3 mm/rev to 1 mm/rev.

Figure 4 shows a graph characterising the change in cross-sectional area at different axial feeds for the same tool position. Analysis of the data shows that the cross-sectional area of the cuts on the output and tip blades of the cutter increases almost directly in proportion to the increase in feed, while for the input blade it remains almost constant.

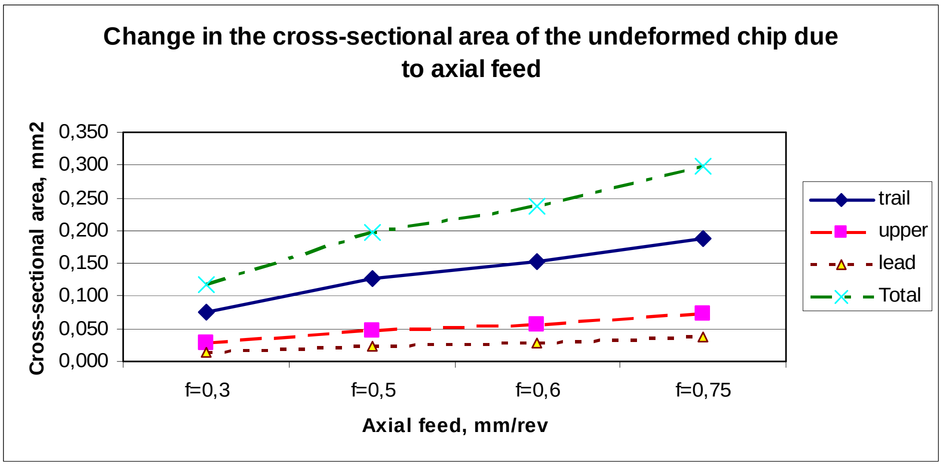

Fig. 4 Change in the cross-sectional area of the undeformed chip due to axial feed for internal gear

To ensure normal cutting conditions, it is necessary for the radius of curvature of the blades to be less than the thickness of the cut, otherwise the allowance will be crushed rather than cut. Based on this, the graph (Fig. 5) shows the minimum allowable radius of curvature for the following initial data. The criterion for the minimum radius is the average thickness of the cut. This is particularly true for the entry part of the cutter, where the thickness hardly changes during cutting and is close to the value of 0.02 mm.

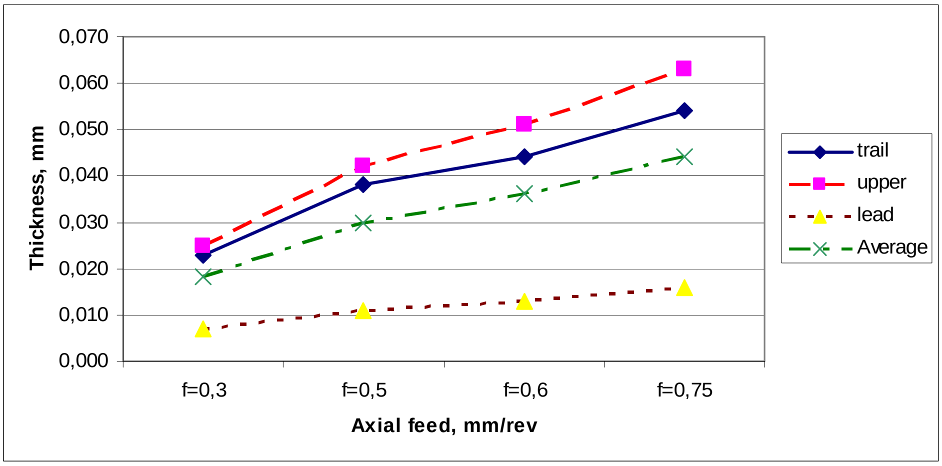

Fig. 5 Change in the thickness of the undeformed chip due to axial feed for internal gear

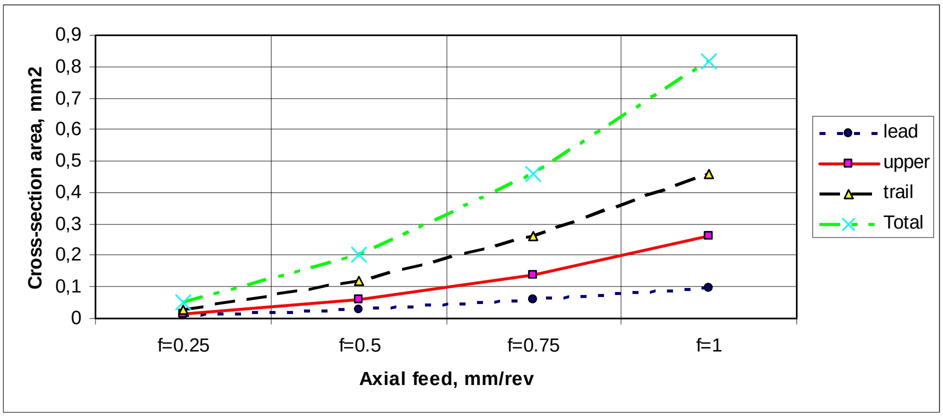

Fig. 6 Change in the cross-sectional area of the undeformed chip due to axial feed for external gear

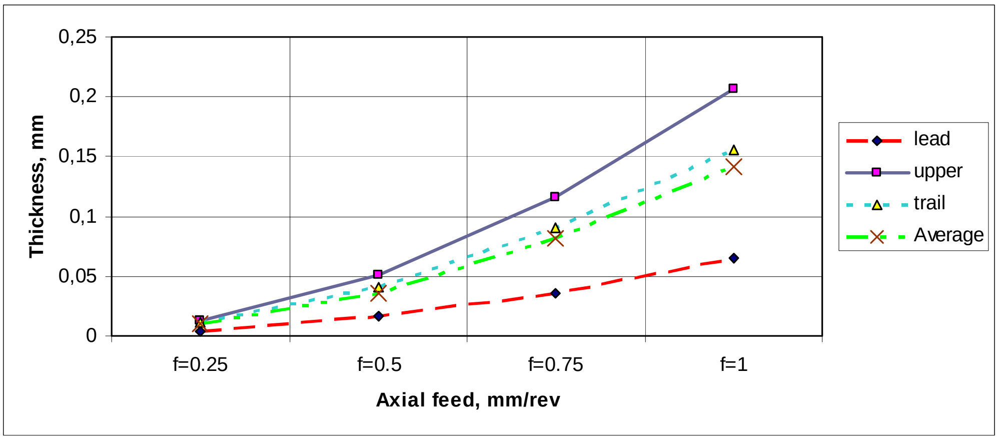

Fig. 7 Change in the thickness of the undeformed chip due to axial feed for external gear

Such investigations can also be carried out for different axial tool feeds, at different tilt angles, for cutting gears with different modules and tooth numbers.

Conclusions

Analysis of the data obtained shows that the thickness of the slices depends significantly on the axial feed rate.

The variation in chip thickness during the cutting of an external gear is similar to that of an internal gear, but the geometric dimensions are significantly larger (almost three times as shown in Figures 4 and 6). However, the cross-sectional areas of the cuts are almost comparable. This means that the chip width formed during the cutting of an external gear is proportionally smaller than that of an internal gear.

As can be seen from Figure 4–7, the thickness values are greatest at the top of the chip, indicating that the upper blade of the cup cutter is cutting most of the material. The effect of the feed rate on the shape change and geometry of the undeformed chip was also considered. In all cases, the cutting process starts from the entry blade and then the upper blade starts to work as it approaches the vertical. The following conclusions can be drawn from the graphs (Fig. 4–7):

– the chip thickness on the top blade of a cup cutter is usually the largest among the other cutter blades (under all the same tool operating conditions).

– the chip cross sectional area is the largest on the trail blade. This is because although the thickness on the top blade is greater, the area is dominated by the length of the trail blade. The lead blade hardly cuts at all and has both the smallest area and the smallest thickness.

– looking at the effect of the feed rate (Fig. 4–7), it can be confirmed that as the feed rate increases from 0.3mm/rev to 0.75mm/rev, the thickness and area increase for each of the blades. Increasing the axial feed also results in an increase in both chip thickness and chip cross-sectional area in all sections. While this effect is not significant for the lead blade (thickness difference is up to 0.04 mm), a linear growth dependence is observed for the upper and trail blades.

In all the simulations performed, the effect of axial tool feed on the thickness and cut area of the undeformed chip is the greatest, demonstrating the direct relationship between feed rate and chip shape. As the free flow zone around the gear is limited in many cases, large lead angles are not always achievable. In all cases, maximum chip thickness and area were observed in the final stages of the cutting process. During the cutting process, the upper part of the cutter experienced the maximum load.

The graphical and analytical dependence of the area or thickness of the undeformed chips on the axial feed, the modulus and the angle of inclination of the tool allows the technologist to select the optimum technological parameters for cutting the gear ring for the corresponding equipment. It is known that the cutting area of an undeformed chip is directly related to the cutting force and the required motor power of the equipment.

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