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RESEARCH ON THE CHARACTERISTICS OF GEAR-CUTTING PROCESSES FOR EXTERNAL AND INTERNAL MESHING USING THE POWER SKIVING METHOD

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Abstract. The results of modelling and investigation of external and internal gear-cutting processes using the power skiving method are presented. The principles of constructing a geometric model of undistorted chip formation are described, based on parameters from which cutting forces are calculated. It is found that, under identical conditions, the cutting force is three times greater when internal gears are cut than when external gears are cut. The influence of this force on the machining error is determined by the gear pitch parameter. It is shown that the most rational way to reduce the machining error is to reduce the cutting force by reducing the axial feed rather than by increasing the number of passes.

Keywords: external and internal gears, power skiving process, undeformed chip, simulation, cutting force, comparison, machining error.

Introduction

Recently, power skiving has become increasingly popular in the manufacture of external and internal gears. This is due to its advantages over traditional methods such as gear hobbing and gear shaping. These advantages include wide versatility, high cutting speed, minimal idle strokes, high productivity, machining accuracy and gear surface quality. However, this technology places higher demands on the quality of the equipment and cutting tools. The power skiving process involves significant cutting forces, which can lead to the risk of vibration, oscillation and elastic deformation on the "tool-workpiece" axis. As a result, machines must have highly synchronised and powerful drives, high rigidity and vibration resistance. In addition, tool life is limited. Under these conditions, there are a number of practical challenges to overcome when developing gear-cutting operations, such as selecting the correct feed and cutting speeds, determining the number of working strokes, the tool spindle tilt angle and ensuring optimum cutting tool geometry. A critical factor in this process is the cutting force and its components. Cutting force depends on cutting parameters, machine characteristics, setup parameters and insert angles, and accuracy, productivity and tool life depend on its magnitude. With this in mind, the aim of this article is to investigate the characteristics of the cutting and forming processes and the influence of the cutting force on the accuracy of the primary gear pitch when cutting external and internal gears.

Review of primary sources

The significant advantages of power skiving over traditional gear-cutting methods have led to extensive research. Analysis of primary sources, focusing on the cutting layers and the cutting force, has revealed the following:

Due to the complexity of this process, the authors resort to certain simplifications when modelling the chip geometry, if they do not take into account one or another element of the kinematics. For example, in [1–4] the auxiliary motion, the rotation of the workpiece is not taken into account. However, power skiving reproduces the kinematics of a gear and pinion, where both elements rotate simultaneously and the cutting and profiling is performed during continuous rotation. This simplification distorts the true shape of the chip and its dimensions.

A different approach to the kinematics of power skiving is reported in [5]. Here the movement of the cup tooth is considered to be similar to the movement of a hob tooth, i.e. around an axis lying in a plane parallel to the gear face. In power skiving, however, the tool axis is in a plane perpendicular to the gear face. Obviously, the modelling results will be inadequate. The same approach is described in the "flat section" method in [6]. Article [7] describes a method for calculating chip thickness in power skiving, but again the shaping is considered as an analogue to hobbing.

The method based on the construction of a mesh in the gap between the teeth to be machined [6] also does not fully take into account the kinematics of this process. This is due to the fact that this mesh is assumed to be stationary with respect to the tool, whereas, as mentioned above, the gap between the teeth makes a continuous circular movement with the gear.

When calculating the cutting force, the authors of the studies also use simplified approaches. For example, in [8] the cutting force is represented by its components. However, the values of these components are determined using coefficients obtained from experimental data. In [4, 8, 10, 11] the cutting force is represented only as a function of the chip thickness. At the same time, although chip thickness is an important cutting parameter, it only determines the intensity of deformation of the allowance when it is converted into chips. An additional and more complete cutting parameter is the chip cross section, which ultimately determines the cutting force. Therefore, this approach to calculating cutting force is limited and does not provide a complete picture of this parameter.

The correct estimation of cutting speed and cutting force vectors has a significant impact on the cutting process. Based on the principles of cutting theory, the resulting cutting speed vector is the geometric sum of the main and auxiliary cutting movements, i.e. the cutting speed and the axial feed rate. Both vectors are related to the cutting tool. However, in well-known studies of the power skiving process, in particular [1, 6], the resulting velocity vector is defined as the geometric sum of the linear velocity vectors of the cutter and the wheel being machined. Incorrect consideration of this vector will lead to an error in the calculation of the geometric parameters of the tool and the cutting force.

To quantify the cutting force, the specific cutting force is often used to describe the force required to cut an area of 1 mm^2. The specific cutting force is a function of the thickness of the layer being cut and can vary widely even within a single cut of variable thickness. This effect is described in [4], but there are no recommendations for calculating the specific cutting force as a function of chip parameters.

Research Results

Let us formulate an algorithm to solve the problem. The modelling of the mechanical, thermal, tribological and dynamic processes and phenomena that accompany the cutting process is based on the parameters of the cuts. Based on this, the sequence of actions that will provide a comprehensive analysis and systematic overall evaluation of the cutting process should include the following

– geometric modelling of undeformed chips;

– determination of the cutting parameters: area, thickness and width of the cuts, length of contact between the blades and the surface to be machined;

– determining the intensity of deformation of the metal layer when it is transformed into chips;

– formation of dependencies for the calculation of the cutting force and its components in the respective surface treatment method;

– using the obtained dependencies for further modelling and calculation of elastic deformations and machining errors, friction forces, heat and temperature on the tool working surfaces, study of elastic vibrations and oscillations in the elastic system of the machine tool, prediction of blade wear, assessment of the impact of these processes on machining performance.

The primary task of comprehensive cutting process modelling is therefore to create a spatial geometric model of undeformed chip formation. This task becomes particularly challenging when dealing with processes with complex kinematics, where a certain number of teeth and their edges, along with multiple cutting motions, are simultaneously involved in cutting and forming processes. Power skiving falls into this category. The cutting and forming of tooth profiles in this process is achieved by the rotational movement of the tool, which generates the cutting speed synchronised with the rotational movement of the workpiece (circular feed), the axial feed typically provided to the cutting insert and an additional movement of the tool relative to the formed surface resulting from the intersection of the axes of the cutting tool and the workpiece. In a gear pair engagement, such as the one reproduced in this process, this movement would cause increased friction. In power skiving, however, it is a necessary condition for cutting.

Geometric model of the 3D chip

An original approach developed for worm gear hobbing [12] was used to develop this model. The approach consists of reproducing the traces of tool movement at each tooth position and at the positions occupied by the cutter in the axial feed path, corresponding to the angular position of the tooth and the corresponding angular position of the traces of the surface that partially formed the recess in the previous cutting cycle. The continuous cutting process is thus represented as a sequence of discrete positions of the tool face in angular and linear tool and workpiece displacements according to the kinematics of a specific process. In contrast to worm gear hobbing, in power skiving the cutter tooth continues cutting in the same recess after the cutter has moved not by the amount of axial feed f_a but by a distance equal to $f_a \cdot i$, where i is the transmission ratio in tool-workpiece engagement. This movement corresponds to one cutting cycle in axial feed and the second cutting cycle corresponds to the angle of rotation of the cutter in final engagement with the wheel.

By superimposing these traces, their intersections with the contour of the face of the tooth in its current position in axial and angular feed are found. This approach allows us to determine the shape of the transition surface formed by the cutter in previous cutting cycles. This surface determines the internal shape and size of the chip, i.e. the cutting thickness at the edges of the tool tooth. It also allows us to determine the performance of these edges and their contribution to cutting and shaping the specified surface, in our case the recess between the workpiece teeth and the side surfaces of the tooth. An integral 3D model of the undeformed chip is created from the successive sections formed at successive cutting positions.

The shapes of the chips obtained from external and internal gears using this method are shown in Fig. 1. Visually, they correspond to the shapes of real power skived chips that are widely available on the Internet.

The shape of the chips indicates that in both cases the major part of the allowance is cut by the cutting edge and the smallest part is cut by the entering edge. The chip formed when internal gears are cut is longer, which can be explained by a greater end contact ratio.

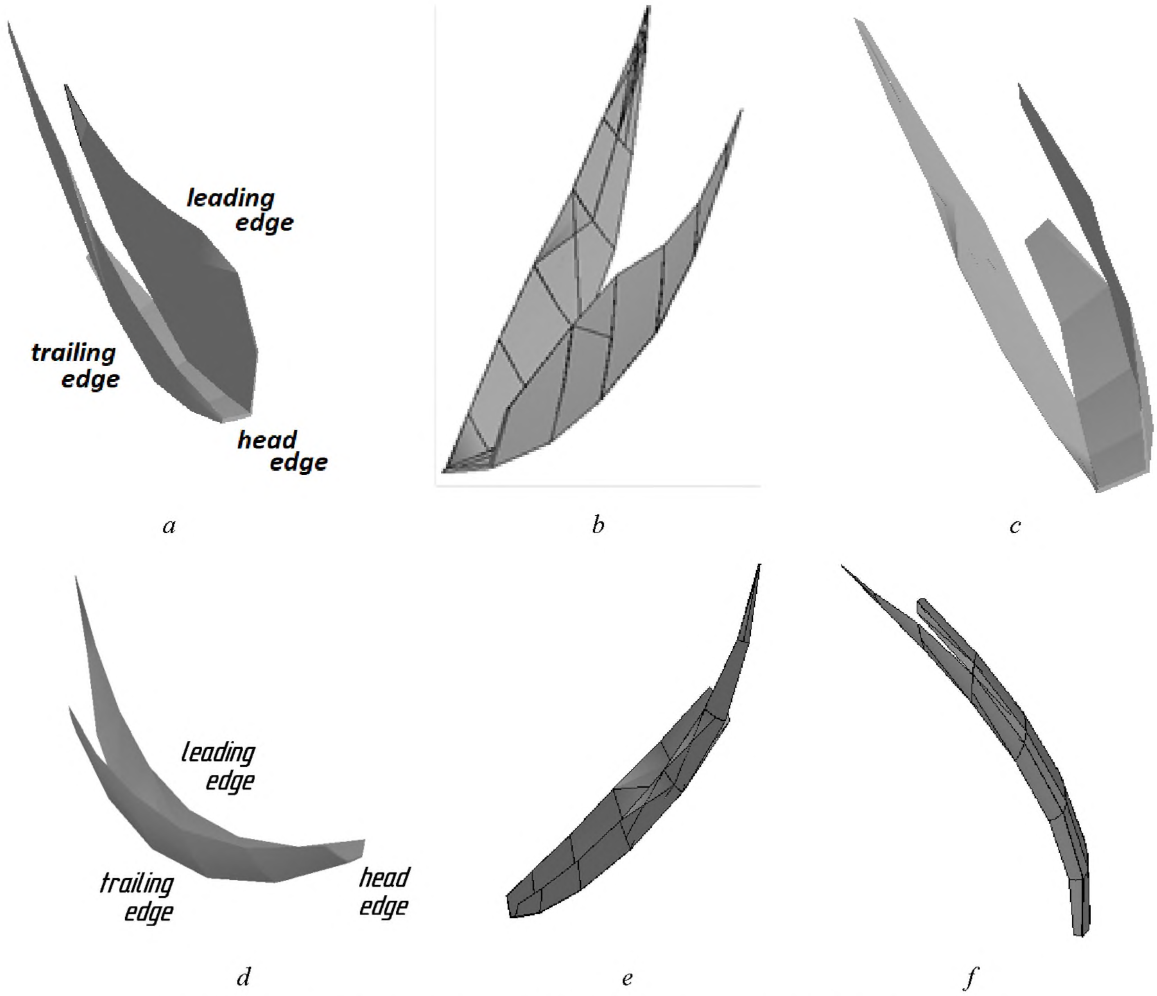


Fig. 1. 3D model of an undeformed chip: a–c – external chip; d–f – internal chip

Cut parameters

Quantitative parameters of the chips in the form of graphs of the cross-sectional area and thickness of the cuts are shown in the Fig. 2.

Initial data:

Gears: Involute spur gears, both external and internal.

Module: m = 2.5 mm

Number of Gear Teeth: Z_g = 33

Number of Cutter Teeth: Z_t = 24

Axial Feed: f_a = 0.75 mm/rev

Depth of Cut: 2m, the last profiling cut

Spindle Angle Setting: 250

Cutting Speed: 100 m/min

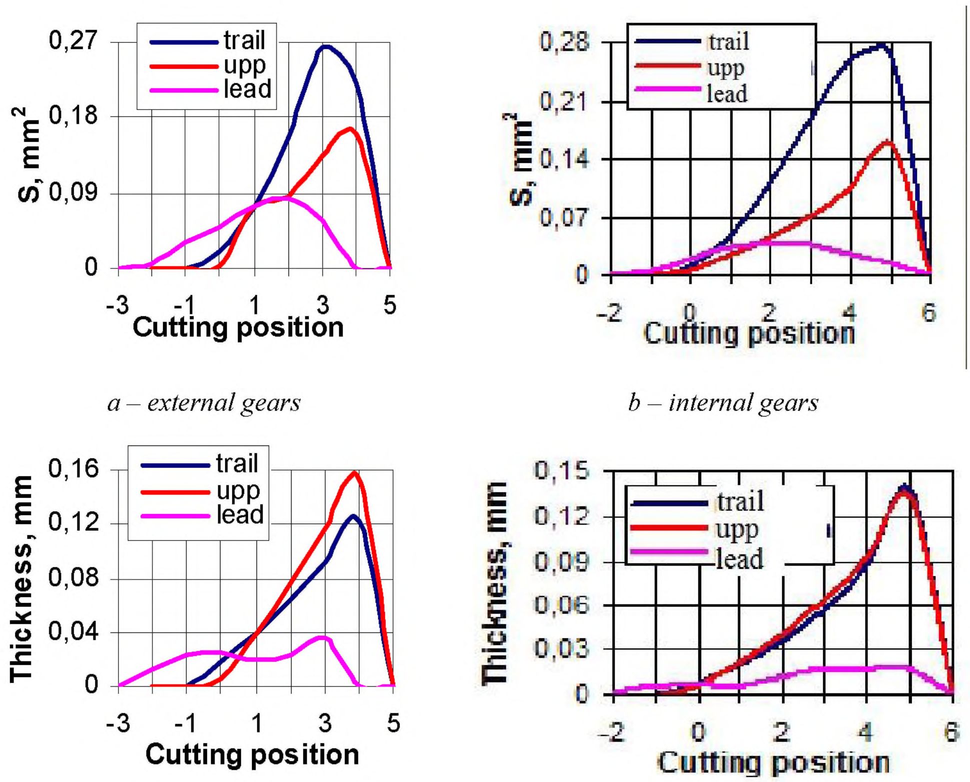
Cutter Outside Diameter: D_{a_h} = 66 mm

Width of the Gear: 22 mm

For the given initial conditions, the final contact angle is 3.25 for the external gear and 6.86 for the internal gear. The engagement zone is divided into 13 successive angular positions, marked -6, -5, ... 0, +1, +2, ... +6, where the zero position coincides with the interaxial line, which serves as the axis of symmetry for the central recess of the gear and divides the engagement zone into left (entry) and right (exit) sections.

The following conclusions can be drawn from the data obtained.

In steady state cutting, the cutter tooth begins to cut the oversize in a separate recess, not at the initial angular positions, but at the entry section close to the interaxial line. As the cutter tooth continues to move, the cutting parameters on all three edges increase rapidly. The cutting edge removes the largest part of the allowance, while the entry edge removes the smallest part. The maximum cross-sectional area and thickness of the cuts are observed in the angular position of the tooth close to exiting contact with the workpiece. Overall, these parameters do not differ significantly between external and internal gears in terms of total cut area and average cut thickness on the tooth. The only difference is that when cutting internal gears, the active cutting area is shifted by one tooth towards the exit side in relation to the axial line. (Fig. 2)



a – external gears *b – internal gears*

c – external gears *d – internal gears*

Fig. 2. Cross-sectional area (a–b) and cut thickness (c–d)

Cutting force

According to the basic principles of cutting theory, the cutting force P_τ is a function of the chip area S_τ (mm^2), the shear strength of the workpiece material and the intensity of chip deposition:

$$P_\tau = [\tau] \cdot S_\tau \cdot \xi \quad , \qquad (1)$$

where: ξ is the chip thickness ratio, $[\tau]$ is the ultimate shear strength of the workpiece material in MPa, Φ is the rake angle.

The value of this coefficient is determined by the formula:

$$\xi = ctg\Phi \cdot \cos\gamma + \sin\gamma \, , \qquad (2)$$

where: γ is the front rake angle. At a zero front rake angle, $\xi = ctg\Phi$.

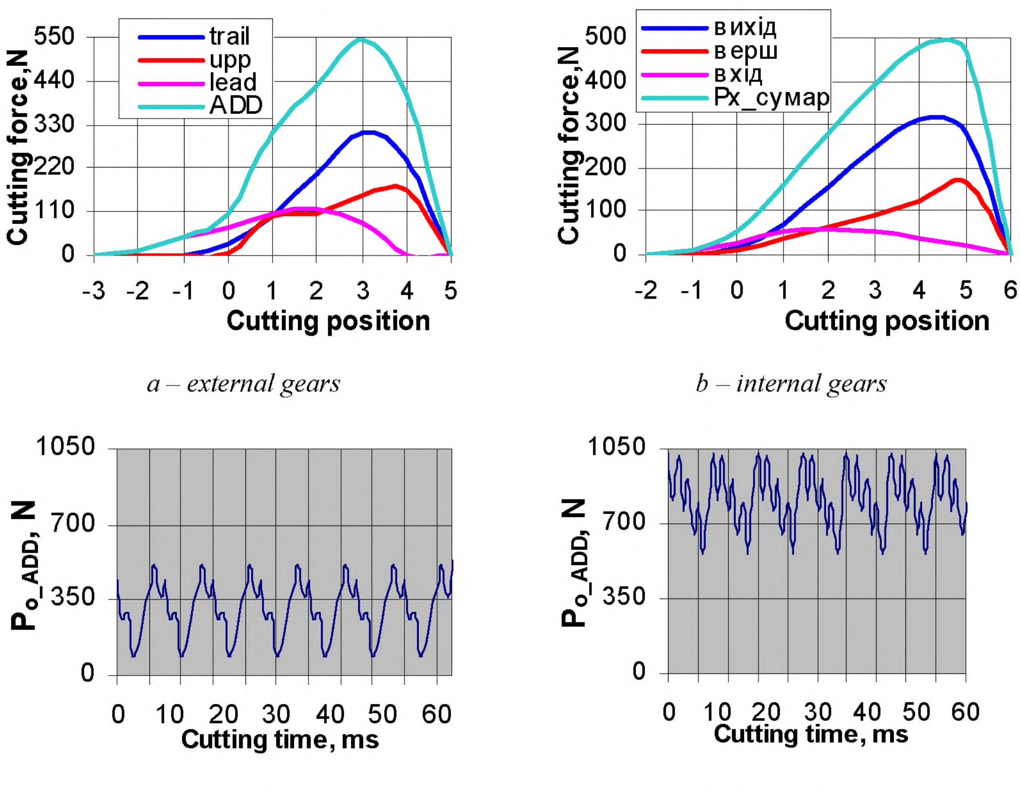
Contrary to the Western school of cutting theory, the value of the chip deposition coefficient ζ is assumed to be equal to the chip thickening ratio, i.e. greater than one.

From the cutting force, we can move to the cutting force component P_o, which coincides with the direction of the cutting speed and is called the principal cutting force component. The chip area S_τ is related to the cross-sectional area of the chip S by the equation: $S_\tau = \dfrac{S}{\sin\Phi}$, and the force P_o is given by: $P_o = P_\tau \cdot \cos\Phi$. Taking these expressions into account, the main component of the cutting force can be described as follows:

$$P_o = [\tau] \cdot S \cdot \xi \quad . \tag{3}$$

The value of the chip deposition coefficient ζ for a given workpiece material and chip thickness ratio can be found using the Deform 2D system [13].

For the given initial data, graphs of the cutting force *Po*, which represents the cutting force on the edges, and the total force on the tooth for external and internal gears are shown in Fig. 3 (*a*, *b*). In both cases, the cutting force values are not significantly different. However, the total force resulting from the simultaneous cutting of several teeth within the engagement angle zone varies significantly (Fig. 3 *c*, *d*). The graphs are shown on the same scale for comparison. It can be seen that as the overlap coefficient and the number of teeth machined increase, the average force and its amplitude increase significantly when cutting internal gears, by 3.4 times (1050 N compared to 310 N) and 1.1 times (235 N compared to 215 N) respectively.



a – external gears *b – internal gears*

c – external gears *d – internal gears*

Fig. 3. Cutting force P_o on the blades as a function of the type gears in successive angular positions of the cutter and a total force in oblique cutting (a–b); total cutting forces in continuous gear machining (c–d)

Let's look at the diagram showing the forces acting on the workpiece and the tool. The tangential component of the cutting force acting on the workpiece (Fig.4), which produces a torque about its axis, is given by the equation:

$$P_{z\_g} = P_o \cdot \sin\omega \cdot \cos\omega = 0.5 \cdot P_o \cdot \sin 2\omega \,. \tag{4}$$

The tangential force acting on the cutter is:

$$P_{z\_tool} = P_o \cdot \sin\omega \,. \tag{5}$$

The angle characterising the elastic interference between the tool and the gear, which causes these forces, depends on the torsional rigidity of the spindle assembly (J_T) and the rigidity of the machine table with the gear (J_G). It can be calculated as follows:

$$\Delta\phi = \frac{T_G}{J_G} + \frac{T_T}{J_T} = \frac{P_{z\_g} \cdot R_{\omega\_g}}{J_G} + \frac{P_{z\_t} \cdot R_{\omega\_t}}{J_T} \,, \tag{6}$$

where T_G and T_T are the torque on the gear and cutter shaft, in Nm, and R_{ω_g} and R_{ω_t} are the respective dividing radii of the gear and cutter, in meters:

$$R_{\omega\_g} = 0.5 \cdot 10^{-3} \cdot m \cdot Z_{gear};\ R_{\omega\_t} = 0.5 \cdot 10^{-3} \cdot m \cdot Z_{tool} \,. \tag{7}$$

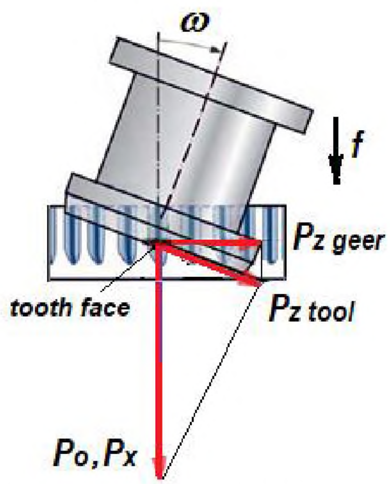


Fig. 4. The kinematical diagram of the Power skiving process

Substituting the given dependencies into equation (6) we obtain the following expression for calculating the angular error caused by the cutting force:

$$\Delta\phi = P_o \cdot m \cdot \left(\frac{Z_{gear} \cdot 0.5 \sin 2\omega}{J_G} + \frac{Z_{tool} \cdot \sin\omega}{J_T} \right) \,. \tag{8}$$

The derived formula can be used to calculate the maximum and average values of the angular error during machining of the gear. Let's assume that the torsional rigidity of the machine spindle assembly is 6.5 kNm/g and the torsional rigidity of the machine table is 9 kNm/g. Based on the previous research and the initial data, the cutting force P_σ is as follows: for external gears, the average force is 311 N and the maximum force is 466 N; for internal gears, the average force is 195 N and the maximum force is 1340 N. The pitch radius of the gear is 41.25 mm and that of the cutter is 30 mm.

Then, according to equation (8), the maximum angular error is 0.12 degrees for the external gear and 0.34 degrees for the internal gear. Graphs illustrating the error in the main gear pitch due to elastic deformation are shown in Fig. 5.

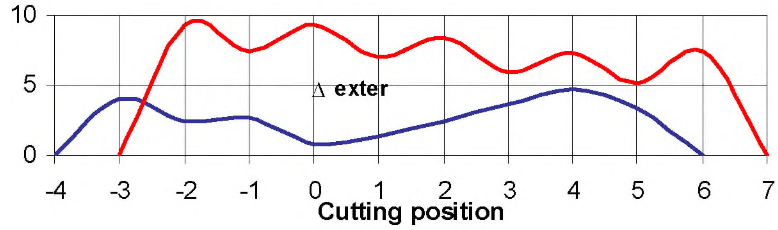


Fig. 5. Error in the main pitch of internal and external gear wheels caused by cutting force and elastic deformation at the tool-workpiece contact line

Analysis of the results obtained

In order to reduce the error, it is necessary to adjust the machining conditions. Possible ways of reducing the error include optimising the tool angles, reducing the helix angle of the cutter teeth and the spindle angle setting, increasing the number of passes and reducing the axial feed. Research shows that changing the tool angles does not achieve a significant reduction in cutting force. Reducing the helix angle of the tool teeth and the spindle angle relative to the wheel axis reduces radial force and cutter deformation, but increases axial cutting force and drive power.

The most effective solution for reducing cutting force and elastic deformation is the latter approach. Specifically, to achieve a maximum error of no more than 0.15 degrees for internal gears, the maximum axial feed for single pass cutting should not exceed 0.23 mm/rev. Therefore, as the modelling results suggest, to ensure consistent accuracy in terms of the main pitch error of the gear being cut, the feed rate should be 3.3 times lower when producing internal gears than when producing external gears.

Such a reduction in feed rate will result in a loss of productivity. Let's determine the cutting time for the options being compared. For the initial data assumed above, the speed of the tool is 482 rpm and the cutting path, taking into account the engagement and traverse, is 56 mm. Then, at a feed rate of 0.75 mm/rev, the machining time for a gear will be 9.3 seconds, and at a feed rate of 0.25 mm/rev it will be 27.7 seconds. If we maintain the feed rate of 0.75 mm/rev and machine the gear in three passes, the machining time, taking into account the increased non-productive time for the transitions, will be 32 seconds. Such a time difference is noticeable for large batches of parts. For example, for 200 parts, the machining time for single-pass and three-pass cutting will be 92 minutes and 106 minutes respectively. From this it can be concluded that the best way to reduce cutting force and associated elastic deformation and achieve maximum productivity is to work with a lower feed and fewer passes. This conclusion applies equally to both internal and external gears.

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