ARCHIVE OF MECHANICAL ENGINEERING

DOI: 10.24425/ame.2024.149636 2024, Vol. 71, No. 2, pp. 213–226

Ihor HRYTSAY [1], Andrii SLIPCHUK [1]

Features of using the power skiving method for multi-pass cutting of internal gears

Received 1 November 2023, **Revised** 12 March 2024, **Accepted** 13 March 2024, **Published online** 9 May 2024

Keywords: internal gear, power skiving, passes, chips, forces

The paper presents the results of a simulation on a 3D model of undeformed chips and cutting forces during three-pass gear cutting using the power skiving method. At the level of individual blades and teeth in successive angular cutting positions, the main component of the cutting force and the tangential force on the cutter axis are shown. The analysis of the forces acting on a single gear tooth and the continuous cutting forces allowed the development of a methodology for the selection of rational cutting modes – the value of the axial feed, the number of passes with different cutting depths in order to ensure the minimum time consumption and to achieve the required accuracy of the gears in terms of the parameter of the permissible angular deviation of the profile of the cut gear. It is shown that, provided the required machining accuracy is ensured, higher productivity is achieved by increasing the axial feed at a lower depth of cut and increasing the number of passes, rather than by reducing the feed and increasing the depth of cut.

1. Introduction

In recent years, the gear manufacturing industry has increasingly used the power skiving method of gear cutting, formerly known as gear turning. Its successful development today has been made possible by the development of high speed, high performance machine drives controlled by CNC systems, which have allowed the synchronization of the working movements that make up the kinematics of this process, as well as the creation of machine structures of considerable rigidity and vibration resistance. The advantages of gear turning over the traditional methods of gear machining, such as hobbing and gear shaping, which are the main methods

✉ Andrii SLIPCHUK, e-mail: andrii.m.slipchuk@lpnu.ua
[1]Lviv Polytechnic National University, Lviv, Ukraine

of manufacturing gears in mass production and small series, are the reduced time wasted to make auxiliary movements, the increased productivity and a higher quality of the gears.

Initially, power skiving was used only on the internal gears of small and medium modules, which had previously been machined by low-productivity hobbing. However, the significant advantages of power skiving over the established gear technologies led to the expansion of its application, the development of machines for the production of external gears, and the extension of this method to the gears of large modules.

At the same time, power skiving technology faces the problem of setting the operating parameters, which include axial feed and cutting speed, as well as the axis crossing angle of the cutter and tool spindle, the geometry of the cutting part and the depth of cut in the passes. The latter is a result of the need to form tooth profiles by means of fast, multiple tool passes, while ensuring the optimum relationship between the depth of cut, the number of passes and the total machining time. By reducing the number of passes one reduces the basic machining time, but increases the cutting force and torque on the workpiece and cutter axes. This increases the level of elastic deformations and vibrations and worsens the surface quality, at the same time incurring a risk of tool tooth failure, i.e., a failure of the technological system. To avoid this risk, it is necessary to reduce the value of feed, which reduces the efficiency of the process.

Considering the rapid development of the power skiving method, it is important to solve the problems described above. In order to do so, it is necessary to study the cutting process of the power skiving method when cutting internal gears in several passes and to formulate recommendations for the selection of its rational parameters.

2. Literature analysis

The most effective solution to this problem is to model the cutting process and to study it using computer tools. The development of the model should include a number of successive stages, including the modelling of the cut layers and the calculation of their parameters, the methodology for calculating the power factors of the process and determining their impact on the parameters of efficiency and reliability of the operation. The analysis of publications on this subject revealed the following.

Due to the complexity of the investigated process, the researchers resort to certain simplifications when modelling the chip geometry, by ignoring some of the elements of the kinematics. For example, in [1–3] the auxiliary motion of the workpiece rotation is not taken into account. However, power skiving involves the kinematics of the gear and the pinion, where both elements rotate simultaneously and cutting and profiling are performed during continuous rolling. The mentioned simplification distorts the actual shape of the chip and changes its dimensions.

In [4], the cutting force is described on the basis of its average values obtained by measurement, and the refinement of this force as a function of the chip thickness and the clearance angle of the cutter is proposed on the basis of appropriate coefficients. This approach does not provide the necessary flexibility when studying the cutting force, because this force is a function of various initial data and machining conditions.

In [5], the chip parameters in the power skiving method are derived by considering the position of the leading surface of the tool tooth during successive transitions with a change in depth of cut, but it is not described how the change in these parameters is taken into account during the continuous rolling of the cutter with the workpiece.

In a number of works, in particular [6–9], the cutting force in the power skiving method is presented as a function of chip thickness only. However, 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 the cutting force is limited and does not give a complete picture of this parameter.

In [5] and [6] the cutting force is considered on the basis of the specific cutting force. However, the specific cutting force is a function of the chip thickness ratio, the value of which is not constant and varies according to the cutting mode and the thickness of the cut. Since in power skiving the thickness of the cut varies with the angle of rotation of the tool tooth, the calculation of the cutting force based on the intensity force is only approximate and estimative.

In the paper [6], the geometry and dimensions of the undeformed chips for internal and external gears machined under various conditions are also presented. However, there is no comprehensive mathematical model for the design and analysis of gear cutting tools. The shape and dimensions of the transition surface formed in the gap between the tool teeth in the previous axial position of the tool along the feed movement are not taken into account.

A similar approach to modelling the parameters of the cuts is presented in [10]. From the analysis of the graphs of the cross-sectional area and thickness of the cuts in this paper, obtained on the basis of the above approach, it follows that the maximum parameters of the cuts – cross-sectional area and thickness, as well as cutting force and strain work, respectively – are assigned to the tool tooth when it is on the centre line.

This conclusion is not true, according to what is shown by the high-frequency images of the chip formation process in the power skiving method [11].

Paper [3] presents the results of an experimental study of the cutting force in the process of nonstationary cutting during cutting-in. These results were also used to determine the correction factors for calculating the cutting force in the power skiving method based on the intensity cutting force.

A similar solution to the problem of modelling the power skiving method, combining the calculation of cutting parameters and the cutting force with experimental results, is proposed by the authors of [7], where the components of the cutting force in gear turning are calculated on the basis of experimental coefficients linked to the cutting parameters. Again, a significant drawback of such methods is that the research results are strictly linked to the conditions under which the experimental studies were carried out.

Common to most of the above papers is that the cutting motion of a single tooth of a skiving cutter is identified with the working motion of a single tooth of a hob [5–7, 10, 12–18]. However, the kinematics of the power skiving process reproduces the meshing of two gears with crossed (schematic) axes, and the rotation of the tool and the workpiece takes place around these axes. The rotation of the skiving tooth is therefore on a circular path relative to the cutter axis, which for spur gears forms an angle of intersection with the workpiece axis equal to the cutter helix angle, i.e., $20^\circ - 25^\circ$. The reciprocal rotation of the tool and workpiece machines the left and right involute profiles of the teeth, the gap and the transition surface.

In hobbing, the angle of intersection between the axes of the hob and the work gear is $65^\circ - 70^\circ$. In other words, in both cases the cutting process is oblique, but the angle between the tool face and the cutting speed is $20^\circ - 25^\circ$ for hobbing and $65^\circ - 70^\circ$ for power skiving. Consequently, the skiving cutter has a longer cutting path and undeformed chip length. It follows that with this approach to kinematics evaluation, the results of the simulation of the parameters of the power skiving process will not correspond to the actual values.

3. Research results

The simulation of contact, force, thermal, tribological and dynamic processes and phenomena accompanying the cutting process is based on the parameters of the cuts. On this basis, studies have been carried out to provide a comprehensive analysis and a systematic overall evaluation of the cutting process:

- geometric modelling of undeformed chips;
- determination of the cutting parameters: area, thickness and width of the layers to be cut off, length of the contact between the blades and the surface to be machined;
- determination of the deformation intensity of the metal layer when it is transformed into chips;
- formulation of dependencies for the calculation of the cutting force and its components in the respective surface treatment;
- study of the complex influence of machining process parameters on the efficiency of a technological operation.

3.1. Geometric model of 3D chips

The task of creating a spatial geometric model of an undeformed chip is most difficult when dealing with processes with complex kinematics, where a certain number of teeth and their blades are simultaneously involved in cutting and forming, combined with several movements that result in cutting. Processes with complex kinematics include power skiving. The cutting and shaping of tooth profiles in this process is performed by the rotary movement of the tool, which generates the cutting speed, the rotation of the gear workpiece coordinated with this movement (circular feed), the axial feed provided in most cases by the cutter, and the additional movement of the tool relative to the formed surface resulting from the intersection of the axes of the cutter and the workpiece. This movement would cause increased friction in the meshing of the gears, but in power skiving it is a necessary condition for cutting.

The graphical-analytical model of the 3D undeformed chips in power skiving is based on the approach developed earlier for the gear hobbing process [19]. It consists in reproducing in each position of the tool tooth the traces of movements in its current position, as well as in the positions taken by this tooth on the cutting path in the 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 process is thus represented by a sequence of discrete positions of the tool face in the angular and linear displacements of the tool and the workpiece according to the kinematics of a particular method. In addition, the contours of the tool tooth trace in the same gap are taken into account as the tooth cuts through the workpiece in the cutter position preceding the axial feed. In contrast to hobbing, in power skiving the cutter tooth continues to cut in the same gap after the cutter has been displaced not by the value of the axial feed rate f_a, but by a distance equal to $f_a \cdot i$, where i is the gear ratio in the tool-workpiece gearing. This displacement corresponds to one cutting cycle at the axial feed rate. The second cutting cycle corresponds to the angle of rotation of the cutter within the overlap ratio with the working gear.

By superimposing the contours of these traces, one can find their intersection with the contour of the tooth face in its current position at axial and circular feeds and the angles of rotation relative to the gear. This approach makes it possible to identify 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 thickness of the cut on the tool's cutting edges. This solution allows one to accurately determine the contours of the chip cross section at a given cutting position, as well as to identify the operation of these blades and their involvement in cutting and shaping the tooth surface.

The influence of the transition surface on the cross-section of the cut layer is shown in Fig. 1.

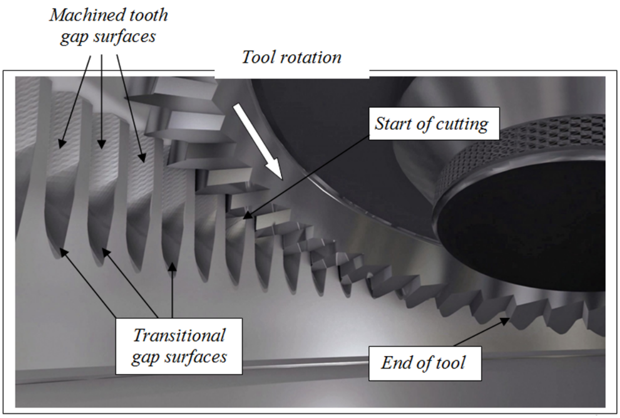


Fig. 1. The surfaces formed during the cutting process and the transition surfaces in the interdental spaces

The actual shape of the instantaneous cross-section of the cut in successive positions of the cutting tooth, which are taken by its front face when cutting in the gap, is determined by the instantaneous contour of the transition surface in its cross-section through the front face of the cutting tooth.

Fig. 2a, b, c shows the instantaneous cross sections for three consecutive passes obtained using this approach. These cross sections are used to design a 3D geometric model of the undeformed chip. Fig. 2d, e, f [2] shows the actual chip for three passes obtained by cutting a gear using the power skiving method.

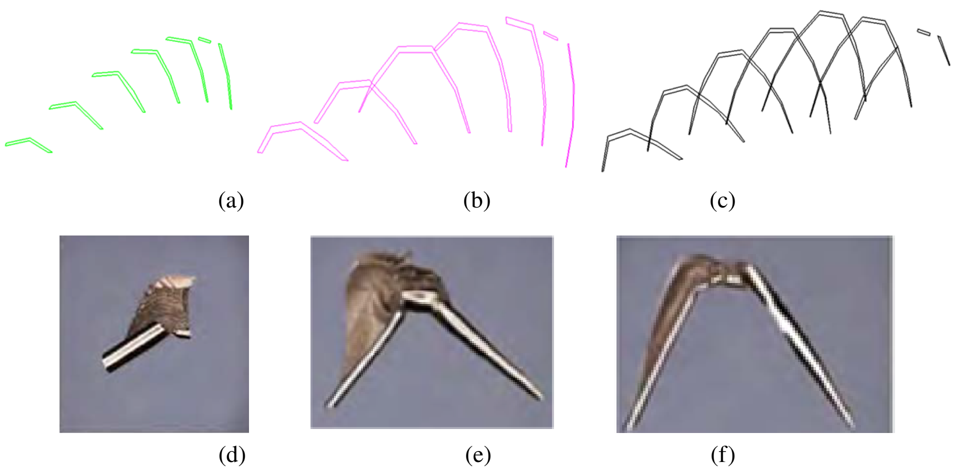


Fig. 2. Sequential cross-sections of undeformed chips in three passes (a–c) and the corresponding chips obtained in the actual process (d–f)

Initial data: involutes spur gear; module 2.5 mm; number of teeth: gear 33, cutter 24; axial feed 0.75 mm/rev; cutting speed 190 m/min; tool's circular frequency

931 rev/min; circular frequency of the gear 667 rev/min; number of passes three; depth per pass: 1 mm, 1.5 mm and 2.5 mm; material of cutter inserts: titanium-tantalum carbide; tool outer diameter 66 mm; width of the tooth rim 22 mm; cutter tooth angle and axis crossing angle 25°; coefficient of friction on the face at this speed 0.63.

The meshing zone of the tool with the gear workpiece is divided into 13 successive angular positions, marked −6, −5, . . . , 0, +1, +2, . . . , +6, with the zero position coinciding with the centre line of a gear meshing.

Based on the approach described above and the model developed on this basis, geometric models of the chips were obtained when the gear was cut in three passes, as shown in Fig. 2.

The parameters of the cuts on the blades in three passes are shown in Fig. 3.

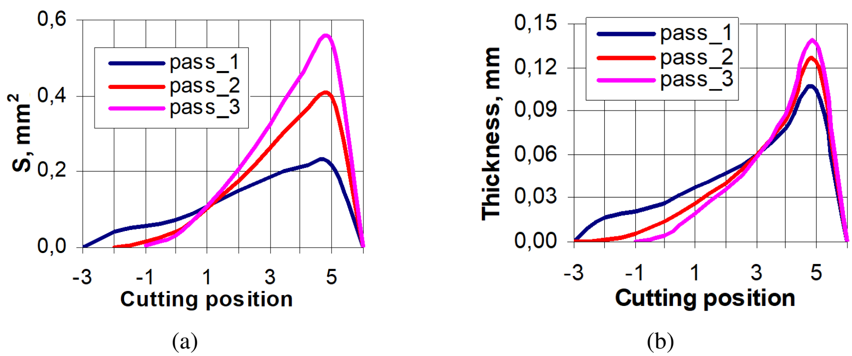


Fig. 3. Cross-sectional area (a) and chip thickness (b) in three passes

3.2. Cutting force

The methodology for modelling and calculating the cutting force in gear turning is given in [20]. According to this methodology, the main component of the cutting force P_o, which coincides with the direction of axial feed and the vector of plastic deformation during cutting, has been determined; this cutting force is represented by the following dependence

$$P_o = [\tau]\, S\xi, \quad \text{N}, \tag{1}$$

where S is the cross-sectional area of the chip, mm^2; $[\tau]$ is the shear limit strength of the workpiece material, MPa; ξ is the chip thickness ratio (the chip shear ratio, or the chip compression ratio), which is the ratio of the chip thickness to the thickness of the layer being machined.

The forces acting on the cutter and gear during power skiving are shown in Fig. 4. They are denoted as P_{z_g} and P_{z_t}, and are the tangential (circumferential) forces acting on the gear and cutter, respectively; P_x is the axial component of the cutting force, whose direction and magnitude coincide with the main component of the cutting force.

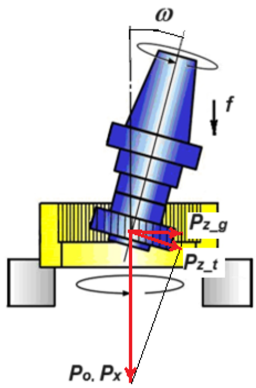


Fig. 4. Diagram of forces acting on the cutter and internal gear during power skiving

The value of the chip thickness ratio depending on the cuts thickness for the corresponding workpiece material and tool was determined using the Deform 2D system [21].

The graphs of the chip compression ratio as a function of cut thickness in three passes are shown in Fig. 5a. The product $[\tau]\xi$ in formula (1) characterizes the specific cutting force, which, according to the graphs (Fig. 5a), has a variable value. This confirms the above hypothesis that the use of the specific cutting force for the calculation of the cutting force on the basis of its average value leads to significant errors.

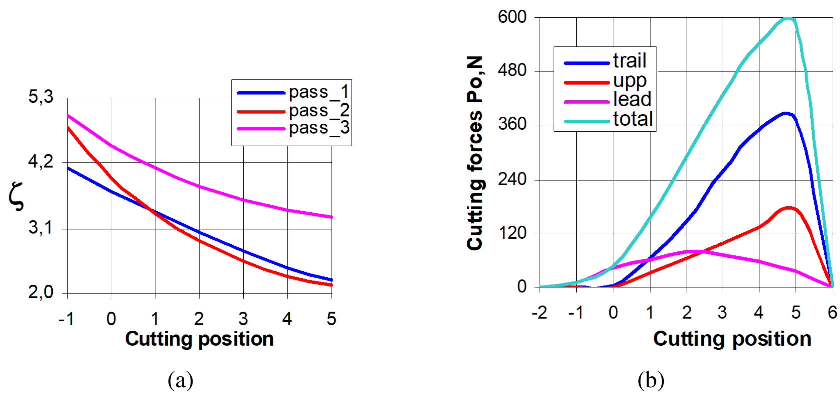


Fig. 5. Chip thickness ratio as a function of the thickness of the cuts in three passes (a) and forces P_o on the tool blades on the second pass (b)

The force P_o applied to the cutting edges during the second pass at successive angular positions of the tool tooth is shown in Fig. 5b. These graphs reflect the forces of a single tooth cutting operation when cutting is performed in a single gap. Comparing the parameters of the cuts and the cutting forces, it can be seen that the cutter removes most of the stock from the gap between the teeth of the gear at the outlet of the contact angle, after the centre line. The maximum force values occurs during the third pass with a cutting depth equal to the full depth: the cutting area on the upper blade was 0.383 mm^2 and the total cutting force on the blades was 586 N.

The total P_{o_tot} forces of continuous cutting are shown in Fig. 6, taking into account the fact that more than one tooth is simultaneously engaged with the gear being machined. For these initial data, where the overlap angle is a contact angle within the overlap of the cutter and gear outside diameters, the ratio of the gear face overlap contact angle to the angular pitch for the passes is 1 – 2.7; 2 – 3.1; 3 – 3.3.

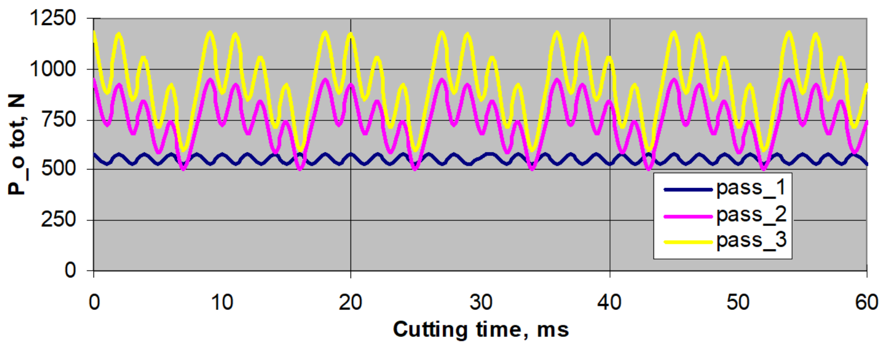


Fig. 6. Total forces P_{o_tot} in continuous cutting on the third pass

In order to determine the force acting on the cutter, it is necessary to consider the tangential force, which generates a torque on the tool axis and causes periodic torsional deformations. To do this, it is necessary to take into account the forces acting on the face of the tool tooth, i.e., the friction forces. Fig. 7 shows a tool tooth and a chip cross section at the i-th angular position of the tooth, characterised by the angle ϕ_t, and the gear, characterised by the angle ϕ_g.

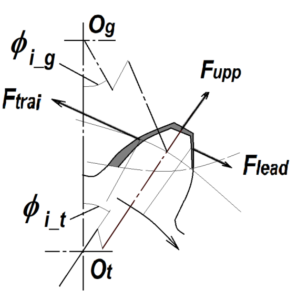


Fig. 7. Friction forces acting on the face of the tool tooth near the cutting edges

The direction of the frictional forces F_{trail} on the trail blade is opposite to the direction of the chip flow. Consequently, the frictional forces on the lead and trail blades are opposite in direction: the frictional force on the trail blade acts in the direction opposite to the rotation of the cutter, while the frictional force on the lead blade coincides with this direction. This results in an increase in the cutting force on the trail blade and a decrease in the cutting force on the lead blade. From this figure it is possible to derive a relationship for calculating the tangential (circumferential) forces P_z acting on the cutting tool on the outer diameter and creating a torque on its axis. The magnitude of such a force generated on a single tooth is:

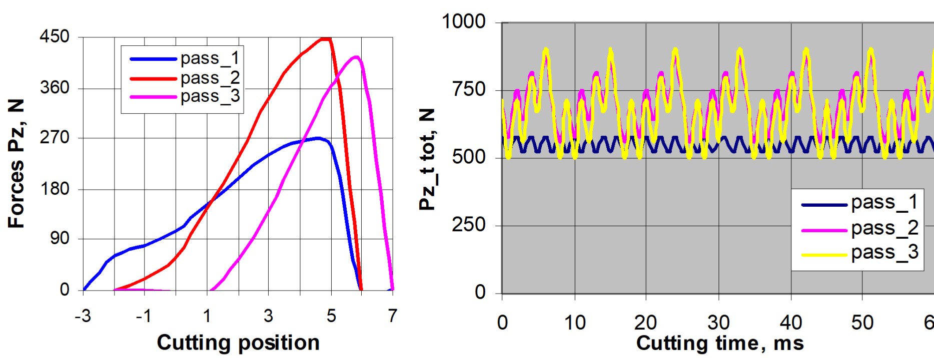
$$P_z = (F_{\text{lead}} - F_{\text{trail}}) \cos\omega + F_{\text{upp}} \cos\phi_{i\_p} + P_{o\_\text{tot}} \sin\omega. \tag{2}$$

Expressing the frictional forces on the face in terms of the force normal to the face and the coefficient of friction μ on that face, we obtain the following formula for calculating the tangential force P_z on a single cutter tooth:

$$P_z = (P_{o\_\text{lead}} - P_{o\_\text{trail}})\,\mu \cos\omega + P_{o\_\text{upp}}\mu \cos\phi_{i\_p} + P_{o\_\text{tot}} \sin\omega. \tag{3}$$

The forces F_i on the side blades act on the point of the centre of mass of the corresponding section of the cut, perpendicular to the radius vector of this point. Taking into account the actual relationship between the size of the tooth tool and the radius of the workpiece tip, these forces are reduced in the calculations to the upper blade at the outer radius of the cutter tooth.

From the results of the study it can be seen that the force P_z acting on the cutter during the first pass is the smallest for both single and multi-tooth engagement (Fig. 8).



(a) (b)

Fig. 8. Tangential forces P_z acting on the cutter during single tooth cutting (a) and total tangential forces of continuous cutting during third pass (b)

As mentioned above, on the first, second and third passes, the ratio of the overlap angles to the angular pitch of the cutter is 2.7, 3.1 and 3.3, respectively.

This means that the frequency of the cutting force P_o and circumferential force P_z and the torque on the cutter axis, which occur during cutting on separate passes, will differ from the tooth frequency, which is a multiple of the number of teeth of the cutter. For the above initial data, the tooth frequency is 931 min^{-1}, i.e., the circular frequency of the tool is 15.5 Hz. Accordingly, the frequencies of the cutting force on the passes will be 42 Hz, 48 Hz and 51 Hz, as shown in the graphs in Fig. 8b. These are low-frequency vibrations with a significant spectral density.

The cyclical force and torque acting on the cutter are external vibration exciters with respect to the machine tool's elastic system and the cutting process. Their negative effect occurs when the machine's elastic system contains a mass (component) with a natural frequency equal to or close to these frequencies, and vibrations in the machine system at these frequencies carry significant energy. In such a case, these forces will have a significant negative effect on the accuracy of the gears. In addition, these vibrations increase the overall cutting path, which reduces the stability of the cutters.

In addition to these negative effects, these forces, due to their average (quasi-static) values, affect machining accuracy by causing elastic deformations in the tool axis. Let us consider how these forces and moments affect the accuracy and efficiency of a gear cutting operation. Suppose that, according to the technical specifications, the tolerance for the angular deviation of the gear profile should be 4.5 angular seconds, i.e., 0.075deg. With an average force P_{z_t} of 696 N on the third pass, its maximum value reaches 907 N, corresponding to a torque on the cutter axis of 29.5 Nm. If the torsional rigidity of the tool spindle of an average power skiving machine is 300 N/deg, the angular error of the gear profile will be 5.9 s, or 0.098 deg, which is outside the tolerance.

Angular profile errors cause variations in axial pitch and uneven speeds in the gear, resulting in increased load and noise in the gear. There are two ways to reduce the cutting force and gear error: by reducing the axial feed rate or by increasing the number of passes while reducing the depth of cut. Modelling of the new conditions shows that by reducing the axial feed rate to 0.47 mm/rev, the force P_{z_t} in the oscillation can be reduced to 684 N, the torque to 23.8 Nm and the gear error to 4.31 s or 0.072 deg. If the number of passes is increased to four, with the depth of cut of 0.5 mm on the last pass, the force P_z will be 713 N, the torque 22.5 Nm and the angular error 0.075 deg. Both changes satisfy the condition of achieving the required accuracy for the specified parameter. However, changing the cutting mode will affect the machining time. Let's determine the machining time required to cut a gear.

With a gear width of 22 mm, the total length of the total cutting path will be 45 mm. The machining time, which is the ratio of the cutting path to the axial feed, is 3.9 seconds for a single pass at a feed rate of 0.75 mm/rev and 15.6 seconds for four passes. Taking into account the additional pass time, the total time will be 24.6 seconds.

With a feed rate of 0.47 mm/rev and three passes, the time for one pass is 6.2 seconds and for three passes, including additional pass time, 27.6 seconds.

For example, if the batch size of the parts is 200, the machining time saving using the first technology option is 10 minutes. Therefore, if the required machining accuracy is to be achieved, higher productivity is achieved by increasing the axial feed rate at a lower depth of cut and increasing the number of passes, rather than by reducing the feed rate and increasing the depth of cut.

Table 1 below compares the two variants of a gear cutting operation, demonstrating the benefits of working at a higher feed rate in more passes.

Table 1. Comparative efficiency parameters for two technological options

<table>
<tr><td colspan="3">Option 1</td><td colspan="4">Option 2</td></tr>
<tr><td colspan="7">Passes</td></tr>
<tr><td>1</td><td>2</td><td>3</td><td>1</td><td>2</td><td>3</td><td>4</td></tr>
<tr><td colspan="7">Cutting depth, mm</td></tr>
<tr><td>1.0</td><td>1.5</td><td>2.5</td><td>0.8</td><td>1.0</td><td>1.2</td><td>2.0</td></tr>
<tr><td colspan="7">Axial feed rate, mm/rev.</td></tr>
<tr><td colspan="3">0.47</td><td colspan="4">0.75</td></tr>
<tr><td colspan="7">Force $P_{z\ \max}$, N</td></tr>
<tr><td colspan="3">684</td><td colspan="4">713</td></tr>
<tr><td colspan="7">The maximum torque on the outer diameter of the tool, Nm</td></tr>
<tr><td colspan="3">23.8</td><td colspan="4">22.5</td></tr>
<tr><td colspan="7">Precision of the tooth profiles:</td></tr>
<tr><td colspan="3">0,072 deg</td><td colspan="4">0.075 deg</td></tr>
<tr><td colspan="7">Machine cutting time, s</td></tr>
<tr><td>6.2</td><td>6.2</td><td>6.2</td><td>3.9</td><td>3.9</td><td>3.9</td><td>3.9</td></tr>
<tr><td colspan="7">Total machine time for all passes, cutting time, s</td></tr>
<tr><td colspan="3">27.6</td><td colspan="4">24.6</td></tr>
</table>

4. Conclusions

1. The Deform 2D computer system was used to study the dependence of the value of the chip shear ratio on the thickness of the cut layers. It is shown that the cutting force as a function of this parameter varies greatly, even for individual blades of the same tooth, and is not constant along the cutting path and the angle of contact between the tool and the workpiece. This means that it is incorrect to use average values of the specific cutting force obtained experimentally under certain initial conditions for the calculation of the cutting force.

2. On the basis of the previously developed graph-analytical model of undeformed chips and chip parameters, the cutting forces in the process of three-pass cutting of gears using the power skiving method were studied. It was found that for the ratios of the cutting depths on the passes used in this technology, the maximum main component of the cutting force occurs on the third pass, and the tangential (circumferential) force on the axis of the cutter – on the first pass.
3. From the results obtained, it can be seen that the main load on the tool tooth is applied to the upper blades and the least to the lead blades. This necessitates additional measures to strengthen the upper blades, for example by selecting appropriate coatings. At the same time, due to the small thickness of the cuts on the lead blades, they will be subject to increased wear, which will require special measures to increase their wear resistance.
4. It has been found that for the power skiving process, for the same machining accuracy, it is more efficient to increase the axial feed and the number of passes while reducing the depth of cut than to reduce the feed, increase the depth of cut and reduce the number of passes.

References

[1] F. Klocke, C. Brecher, C. Löpenhaus, P. Ganser, J. Staudt, and M. Krömer. Technological and Simulative Analysis of Power Skiving. *Procedia CIRP*, 50:773–778, 2016. doi: 10.1016/j.procir.2016.05.052.

[2] H.J. Stadtfeld. Power skiving of cylindrical gears on different machine platforms. *Gear Technology*. 2014(1):52–62, 2014.

[3] B. Vargas, M. Zapf, J. Klose, F. Zanger, and V. Schulze. Numerical modelling of cutting forces in gear skiving. *Procedia CIRP*, 82:455–460, 2019. doi: 10.1016/j.procir.2019.04.039.

[4] H. Onozuka, F. Tayama, Y. Huangb, M. Inuib. Cutting force model for power skiving of internal gear. *Journal of Manufacturing Processes*, 56(B):1277–1285, 2020. doi: 10.1016/j.jmapro.2020.04.022.

[5] M. Inuia, Y. Huang, H. Onozuka, and N. Umezu. Geometric simulation of power skiving of internal gear using solid model with triple-dexel representation. *Procedia Manufacturing*, 48:520–527, 2020. doi: .

[6] N. Tapoglou. Calculation of non-deformed chip and gear geometry in power skiving using a CAD-based simulation. *The International Journal of Advanced Manufacturing Technology*, 100(5-8):1779–1785, 2019. doi: 10.1007/s00170-018-2790-3.

[7] P. McCloskey, A. Katz, L. Berglind, K. Erkorkmaz, E. Ozturk, and F. Ismail. Chip geometry and cutting forces in gear power skiving. *CIRP Annals*, 68(1):109–112, 2019. doi: 10.1016/j.cirp.2019.04.085.

[8] A. Antoniadis. Gear skiving—CAD simulation approach. *Computer-Aided Design*, 44(7):611–616, 2012. doi: 10.1016/j.cad.2012.02.003.

[9] A. Antoniadis, N. Vidakis, and N. Bilalis. A simulation model of gear skiving. *Journal of Materials Processing Technology*, 146(2):213–220, 2004. doi: 10.1016/j.jmatprotec.2003.10.019.

[10] T. Bergs, A. Georgoussis, and C. Löpenhaus. Development of a numerical simulation method for gear skiving. *Procedia CIRP*, 88:352–357, 2020. doi: 10.1016/j.procir.2020.05.061.

[11] https://www.youtube.com/watch?v=0C4hFSeGryM.

[12] T. Nishikawa, S. Shimada, G. Kobayashi, Z. Ren, and N. Sugita. Using power skiving to increase the efficiency and precision of internal gear cutting. *Komatsu Technical Report*, 64(171):1–7, 2018.

[13] C. Janßen, J. Brimmers, and V. Bergs. Validation of the plane-based penetration calculation for gear skiving. *Procedia CIRP*, 99:220–225, 2021. doi: 10.1016/j.procir.2021.03.034.

[14] C.Y. Tsai and P.D. Lin. Gear manufacturing using power-skiving method on six-axis CNC turn-mill machining center. *The International Journal of Advanced Manufacturing Technology*, 95:609–623, 2018. doi: 10.1007/s00170-017-1154-8.

[15] V. Schulze, C. Kühlewein, and H. Autenrieth. 3D-FEM modeling of gear skiving to investigate kinematics and chip formation mechanisms. *Advanced Materials Research*, 223:46–55, 2011. doi: 10.4028/www.scientific.net/AMR.223.46.

[16] E. Guo, R. Hong, X. Huang, and C. Fang. Research on the cutting mechanism of cylindrical gear power skiving. *The International Journal of Advanced Manufacturing Technology*, 79:541–550, 2015. doi: 10.1007/s00170-015-6816-9.

[17] T. Luu and Y. Wu. A novel correction method to attain even grinding allowance in CNC gear skiving process. *Mechanism and Machine Theory*. 171:104771, 2022. doi: 10.1016/j.mechmachtheory.2022.104771.

[18] C.Y. Tsai. Power-skiving tool design method for interference-free involute internal gear cutting. *Mechanism and Machine Theory*, 164:104396. 2021. doi: 10.1016/j.mechmachtheory.2021.104396.

[19] I. Hrytsay, V. Stupnytskyy, and V. Topchii. Improved method of gear hobbing computer-aided simulation. *Archive of Mechanical Engineering*, 66(4):475–494, 2019. doi: 10.24425/ame.2019.131358.

[20] I. Hrytsay, V. Stupnytskyy, A. Slipchuk, and J. Ziobro. Load parameters of the gear machining by power skiving and their influence on the machining system. In: Tonkonogyi, V., Ivanov, V., Trojanowska, J., Oborskyi, G., Pavlenko, I. (eds) Advanced Manufacturing Processes V. InterPartner 2023. Lecture Notes in Mechanical Engineering. Springer, Cham. doi: 10.1007/978-3-031-42778-7_15.

[21] V. Stupnytskyy. Features of functionally-oriented engineering technologies in concurrent environment.*International Journal of Engineering Research & Technology (IJERT)*, 2(9):1181–1186, 2013.