Cutting of worm, spiroid and bevel gearwheel teeth by means of running-in cutter head

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Abstract. The paper considers an alternative to traditional methods of tooth machining for worm, spiroid and bevel gearwheels – by means of an assembled multi-tooth running-in cutter head with hard-alloy inserts. Within the cutting process the cutter head is rotated and fed along its axis concurrently with the rotation of the workpiece, thus implementing the generating worm with a continuous or variable pitch. It is preferable to make the multi-thread generating worm with regard to increasing the production efficiency and valid control of the level of contact localization. The design scheme of setting parameters is considered on the basis of providing the conjugacy at two design points assigned at opposite tooth flanks. The design scheme of the generated tooth geometry is also discussed. Design examples are given to show the possibility of providing the necessary degree of contact localization. The method is implemented at common and simply set metal cutting machine tools – universal gear hobbing machines and machining centres. As compared to traditional methods, the proposed method provides the effective control of tooth geometry, reduction of time and cost of production preparation, especially in the absence of the specialized equipment, staff and corresponding techniques at the production site.

1. Introduction

Gear cutting is traditionally considered as the area of mechanical engineering that requires specific equipment, tools and staff at all stages of the design and production preparation and implementation. Much efforts have been made for the last decades to develop high-efficiency schemes of tooth generating, to design layouts of new cutting tools and to implement tooth machining by means of ample kinematic features of advanced multi-coordinate machines [1, 2, 3, 4, 5, 6]. One of the most complicated subareas of gear cutting is the machining of curvilinear (circular and spiral-type) teeth of bevel gears; its high cost and even unavailability is the stumbling point for many enterprises that prevents them from solving many practical problems. The present work considers certain results of the general solution of the gear machining problem for bevel, worm and spiroid gearwheels. A specific (though relatively simple) assembled gear cutting tool is applied at machining – running-in cutter heads and the set of generating motions. On the other hand, the authors look upon the most effective implementation of the proposed method at multi-coordinate CNC machine-tools. Therefore, the proposed solution combines the approaches that are traditional for gear machining and advanced ones that are related to the mentioned new features of the modern equipment.
2. Basic design equations
The common method applied for gear machining of worm and spiroid gearwheels is the tooth formation by means of the constant pitch generating worm that rotates consistently with the workpiece rotation. The traditional statement implies that the geometry, setting and motion parameters of the machine-tool gearing coincide with the corresponding parameters of the operating gear; therefore, the conjugate linear contact in the gear is provided. However, according to [7, 8], such a contact is more likely to be the drawback of the real gear rather than its advantage, since it is very sensitive to inevitable errors and deformations. In order to provide the correct contact localization along the tooth height and length that reduces this sensitivity, alterations are introduced to the generating parameters of gearwheel teeth and/or worm threads that result in the geometric modification of teeth. The method for calculation of generating parameters (hereinafter – parameters of the machine-tool setting) that was firstly proposed in [9] and that provides the required contact localization found its regular application for cutting spiroid gearwheels for pipeline valve gearboxes [10]. The main idea of this method is that the setting parameters are selected due to:

– the condition of conjugacy [11] for surfaces of the worm, gearwheel and generating worm at design points assigned at tooth flanks of the gearwheel that is precisely conjugate with the worm of the gear:

\[ n_{v_1} = n(v_1 - v_2) = 0, \]

\[ \Rightarrow n(v_0 - v_1) = n n_{v_0} = 0, \] (1)

\[ n_{v_2} = n(v_0 - v_2) = 0, \]

where \( n \) is the common normal line to the three mentioned surfaces, \( v_{0(1, 2)} \) are velocities of their motion at meshing, \( v_{12}, v_{02} \) and \( v_{01} \) are relative velocities (hereinafter indices 0, 1 and 2 are related to the generating worm, operating worm and gearwheel, correspondingly);

– invariant features of helicoid surfaces of worms [9]:

\[ \tan \gamma = -\frac{ne_t}{nk}, \] (2)

\[ \tan \alpha_x = -\frac{ne_t}{nk}. \] (3)

where \( \alpha_x \) is the axial angle of the worm profile, \( \gamma \) is its helix angle, \( e_t, e_r \) and \( k \) are unit vectors of the circumferential, radial and axial directions with respect to the worm axis.

Equations (1) – (3) have a simple solution [9] for which the assigned parameters are the machine-tool interaxial angle \( \Sigma_0 \), the number of threads \( z_0 \) and the axial module \( m_{x0} \) of the generating worm; while the determined ones are the machine-tool interaxial distance \( a_{x0} \), profile angles \( \alpha_{x0} \) and the diameter \( d_0 \) of the generating worm.

The method was expanded for the case of generating the teeth of worm [12] and bevel [13] gearwheels. Machining schemes are shown in Figure 1. Motions necessary for generating – the consistent rotation of the tool (the angle of rotation \( \varphi_0 \)) and workpiece (\( \varphi_2 \)) and the tool feed (\( p_0 \)) – are rather simple and are normally implemented at common gear-hobbing machine-tools. Methods of their setting are also simple and visual.

One of the favorable features of this method was the possibility to reduce the cutting of gearwheels for multithread gears to the application of single- or double-thread hobs. However, in certain cases, multithread generating worms turned to be preferable for generating of the necessary tooth modifications. Here the problem of production and operation of the corresponding hobs that has always been a trouble for manufacturers becomes even worse. It is shown in [14] that this difficulty can be overcome by applying a simpler tool – the flying cutter. This cutting method is usually applied in single-item production and it differs by the simplicity and the rate of tool production. Its main drawback is that the efficiency of gear machining is multiply lower than that of gear hobbing. This problem can be solved by applying the assembled tool – a multi-tooth running-in cutter head (Figure
2) with the abrupt increase of the cutting rate provided by hard-alloy cutting inserts and by separation of the metal excess removed along the opposite flanks of teeth between different cutters of the head. The additional advantage of this method is a simple possibility to separate the metal recess removed from the opposite flanks of teeth.

In its essence, the generating process by means of this tool is similar to the formation by means of the flying cutter: the tool feed is provided along its axis with the corresponding additional turn of the workpiece of the tool itself. Here the cutting edges of cutters are reproducing the multi-thread generating worm. If they are rectilinear, the worm has the rectilinear normal thread profile (ZN1 worms in accordance with the State Standard 18498-89 and SZN 1 – State Standard 22850-77) and the concave axial profile [15]; which also provides the profile modification of the generated teeth. In general case of the tool feed variable within the cutting, the running-in cutter head is reproducing the worm with the variable pitch. Thus, at linear variation of the feed, the coordinates of points of the generating worm that rotates in the coordinate system with the axis $z$ coinciding with the worm axis are subjected to the following relations:

\[
\begin{align*}
  x &= r \cos(\vartheta + \varphi), \\
  y &= r \sin(\vartheta + \varphi), \\
  z &= z_0 + f(r) + p_{\varphi_0}(\vartheta - \vartheta_0) + k_p \frac{(\vartheta - \vartheta_0)^2}{2},
\end{align*}
\]

(4)

where $r$ (radius) and $\vartheta$ are curvilinear coordinates – parameters of the helical surface; $\varphi$ is the angle of worm rotation; $f(r)$ is the function of the worm thread axial profile; $z_0$ is the coordinate of the medium (taken to be the reference one) face section of the worm in which its helical line has the reference helical ($p_{\varphi_0}$) and angular ($\vartheta_0$) parameters, $k_p$ is the coefficient of linear variation of the helical parameter. 

Projections of the normal vector $\mathbf{n}$ to the flank of the generating worm are:

\[
\begin{align*}
  n_x &= -yp_x + xrtana_x, \\
  n_y &= xp_y + yrtana_x, \\
  n_z &= -r^2.
\end{align*}
\]

(5)
where \( p_\gamma = p_\gamma (\theta - \theta_0), \tan a_\gamma = f'(r) \).

Coordinates of points of tooth surfaces formed by the generating worm can be determined by a simple, visual kinematic method [16] that came into common use at analysis of gearing with its basic condition:

\[ \mathbf{n} \mathbf{v}_s = 0, \]  

(6)

where \( \mathbf{v}_s \) is the vector of the relative velocity at generation. The notation in the algebraic form and solution of the equation (6) within searching the points of the generated surface in the coordinate form or parametrically does not mean any significant difficulty.

3. Possibilities of tooth modification control

The main objective at the choice of machine-tool setting parameters is to provide such kind (correct) of tooth geometry for which deviations (modifications) of the generated tooth from the tooth that is precisely conjugating with the gear worm thread would be smoothly increasing from the central part of the flank to edges both along the tooth length and height (profile). This, in turn, will provide the reasonable degree of contact localization in the gear. Different generation methods (except for the trivial linewise formation of the tooth by a spherical end mill) are not commonly suitable for various types of gearwheels. At synthesis of the localized contact the choice of setting parameters is usually an iterative process within which the designing engineer usually gets unsatisfactory distribution of modifications at first approximations; then, he improves it by varying the parameters and correlating with these or those criteria. Therefore, it is important to have the available corresponding means (parameters) of the effective control of this process. Let us show by examples, that the considered method provides the designer with these tools at least for teeth of worm, spiroid and bevel gearwheels.

We will use the so called modification fields (foreign researchers use the term ease-off) for the analysis; they are shown in Figures 3-5 and represented as lines of the modification level on the developed views (projections on the axial plane) of teeth.

Figure 3 shows the examples of failed modifications of worm gearwheel teeth for gears with the interaxial distance 100 mm that have a high gear ratio common for a worm gear (36:1 – Figure 3a) or a relatively small one (36:6 – Figure 3b). The distribution of modifications evidently specifies that in the first case the initial contact is shifted to the tooth apex, and in the second one it is shifted to the right face end and becomes excessively localized along the tooth length. The situation can be improved and modification at tooth edges can be provided within 0.04...0.08 mm by shifting the chosen design point and variation of the relation between the axial module of the generating worm and machine-tool interaxial angle. Note, that we applied the four-thread generating worm (four-thread running in head) for the first single-thread gear and the six-thread worm for the second one.

Similar examples are shown in Figure 4 for the case of generating the teeth of spiroid gearwheels (a gear with the interaxial distance 65 mm). The following features should be paid attention to:

– spiroid gearing is asymmetric, and there can be (and usually are) different unfavorable modifications for the convex (Figure 4a) and concave (Figure 4b) tooth flanks; for instance, modification can be insufficient for one of them and excessive for the other (Figure 4a and 4b);
– when concave flanks are generated, there is the risk of tooth undercutting that is characterized by a relatively large transient segment, and it limits the increase of the generating worm diameter;
– the situation is common when it is impossible to get the correct modification at the double-sided tooth cutting (final formation of both flanks per one pass); the way out is the application of the generating worm with the variable pitch. Its implementation by a hob is certainly implying a significant complication of the technology; however, in case of the running-in cutter and CNC machine-tool it does not mean much of the difficulty.

Note, that in this case the calculation of machine-tool settings is also reduced to multi-thread generating worms – four-thread for a single-thread gear and eight-thread for a six-thread one. It provides the application of multi-thread tools thus allowing to increase the gear machining efficiency. Figure 5 shows the possibilities of modification for spiral teeth of bevel gearwheels with the tooth number 25 by means of a four-thread running-in cutter head. The main features here are as follows:
– it is necessary to apply two running-in cutter heads that implement generating worms for the left and right directions of threads;
– solutions – sets of parameters of machine-tool settings, that provide the correct tooth modification – are within very short ranges (bands) of parameters thus complicating the search;
– the typical defect of modifications is the shift of the area with their minimum values to the tooth heel (Figure 5a, b) as a specific “fishtail”;
– in order to provide the correct modification it is necessary to aspire to the undercut of concave flanks.

![Figure 4. Examples of correction of the failed modification for spiroid gearwheel teeth.](image)

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length and height. As a rule, the excessive modification is caused by the exceedingly large diameter of the generating worm, and it is corrected by variation of the machine-tool interaxial angle and module of the operating and generating worms.

4. Possibilities of the method implementation
Motions necessary for generation are naturally implemented at a gear-hobbing machine-tool; the scheme is shown in Figure 6. In this case, in order to provide the high rigidity, it is preferable to make the shank and double-seat tool.

Certain conclusions can be made on the results of cutting the sample batch of gearwheels – spiroid (Figure 7a) and bevel ones (Figure 7b).

1. Due to separation of the metal excess in pairs of cutters (conventionally, even cutters are machining the concave flanks and odd cutters are for the convex ones) and increased rigidity of the tool, the machining accuracy is considerably higher than in the case of machining by a usual flying cutter. Contact patterns in gears turned to be close to the design ones.
2. The additional factor that increases the accuracy of machining is that it is carried out at fixed vertical and radial guidelines of the gear-hobbing machine-tool.
3. Machining can be carried out with the automatic tangential feed even at the versatile gear-hobbing machine-tool (without CNC).
4. The efficiency of machining turned to be comparable with the efficiency of gear-hobbing by high-speed hobs (the cutting time for a steel gearwheel with the diameter 160 mm and average transverse module of teeth about 4 mm was 15 min), here:
   – for better implementation of possibilities of hard-alloy inserts, one should aspire to higher cutting speeds and lower feeds;
   – the additional reason for feed reduction is that in case of one pass machining the inserts are operating in the non-typical and rigid mode – with almost the whole length of the cutting edge;
   – the machine-tool gear ratio turns to be relatively small (usually within the range 4…10), that is why, the factor limiting the efficiency of machining at the gear-hobbing machine-tool is the allowable rotational frequency of the bench (20…40 rev/min); this factor is even more critical with the increase of the design number of threads of the generating worm.
5. CNC gear-hobbing machine-tools allow for implementing the variable pitch of the generating worm and variable feed of the tool within its cutting-in and cutting-off, thus additionally providing the efficiency increase.
6. Roughness of tooth flanks is considerably higher (the roughness parameter is achieved within the range $Ra_{1.25…1.6} \text{ mcm}$) than that for the worm gear-hobbing; and it can be reduced when minimizing the run-out of inserts.
7. There is the prospect of tooth finishing by means of running-in cutter heads. In this case:
   – in order to minimize the influence of errors of relative arrangement of cutters, it is preferable to make the finishing by two-cutter heads with separation of the removed metal excess along the opposite tooth flanks (or by three-cutter heads with separation along tooth flanks and the root); correspondingly, the design number of threads of the generating worm should be chosen oddly even (or multiple of three for three-cutter heads);
   – machining of heat-strengthened (minimum up to the hardness HRC 50) gearwheels is possible.

The noticed drawback of the method implementation at the gear-hobbing machine-tool is the restriction of the cutting speed that can be increased by means of the hard-alloy tool. It encouraged us to develop a machining scheme for machine-tools like a milling machining center (Figure 9). For this purpose the machine-tool should be equipped with:
   – a high-speed (with a rotational frequency up to 100 rev/min) numerically controlled rotary table;
   – a device for tilting of the rotary table (a hand-driven table which is only positioning is allowable) necessary to adjust the non-orthogonal machine-tool gearing;
   – an “electronic gearbox” program software in order to synchronize the gearwheel rotation and linear displacement of the cutting tool.

In our opinion, it will allow to increase multiply (not less than by 2-3 times) the efficiency of tooth machining by the running-in cutter head. In this case, the latter should be cantilever or mounted.
5. Conclusion
The method of tooth machining for worm, spiroid and bevel gearwheels by means of the running-in cutter head considered in this manuscript has, to our opinion, a good chance to compete with traditional methods (and, perhaps, substitute them in many cases) due to its effective means of controlling the tooth geometry, simplicity and low cost of implementation (including the preparation of production), satisfactory and even increased efficiency, high accuracy and quality of surfaces. Sample machining of gearwheel batches generally gave promising results.

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