SECTION 11. MECHANICAL ENGINEERING

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11.1 Manufacturing of spur gears by a new method of continuous forming with disc milling cutters

Cylindrical gears are used in modern machines and mechanisms used in mechanical engineering, mining, transport, construction, and agricultural industries. The functional characteristics of gears are ensured during gear manufacturing in gear milling operations. Gear milling operations are characterized by high technological cost, which is determined by relatively low productivity, high cost of tools, and significant operating costs. The development of effective technologies for manufacturing cylindrical gears with the necessary functional characteristics is a crucial task in modern mechanical engineering production.

The functional characteristics of modern cylindrical gears, defined by their load capacity and accuracy, are achieved through gear-cutting operations performed on gear-milling machines that utilize worm cutters of the appropriate accuracy classes. Worm cutters are among the most complex and expensive metal-cutting tools. Gear milling with worm cutters on gear milling machines ensures the production of cylindrical gears with an involute tooth profile that has significant limitations in terms of load capacity. The gear milling process using worm cutters involves interdependent cutting and profiling processes, which prevents the intensification of this process. Moreover, the properties of modern tool materials and machines are not fully utilized [533, 534].

Improvement of the operational characteristics of cylindrical gears is carried out by using cylindrical gears wheels with non-involute types of engagements formed by concave-convex profiles of the teeth of the wheels, in particular, the Novikov profile, the S-profile [535-537] and the sinusoidal profile [538-541]. Cylindrical gears with the mentioned tooth profiles are characterized by high-performance indicators such as high load capacity, low vibration and noise levels [541]. However, the previously mentioned cylindrical gears are not widely used because their manufacture is accompanied by significant technological difficulties, which are associated with the lack of appropriate cutting tools or the use of complex, expensive multi-axis machines with CNC [539, 540]. As a result, the development of new technological processes for cutting cylindrical gears with a convex-concave or involute modified tooth profile is one of the promising areas of scientific research.

New tooth cutting processes include a method based on the use of disk cutters (not profiled according to an involute profile), which are given a certain kinematic shaping movement, which ensures the production of cylindrical gears with new concave-convex or modified involute tooth profiles [542-545]. In the new gear cutting process, the disk cutter receives a reciprocating motion in the radial direction of the gear wheel while the gear wheel continuously rotates at a constant angular velocity that is consistent with the reciprocating motion of the disk cutter. The process of obtaining a convex-concave tooth profile on cylindrical gears with a disc-shaped non-profiled cutter can be carried out on traditional gear milling machines. The disk cutter is mounted on the machine tool arbor of a gear milling machine with a certain eccentricity (radial displacement relative to the axis of rotation of the tool arbor), which is determined by the gear module. The gear blank rotates continuously around its axis. Synchronous and mutually coordinated movements of the disk cutter with the rotation of the gear being cut ensure the cutting of teeth with a sinusoidal profile [541-543]. However, this area of research is characterized by the fact that the obtained ratios do not take into account the actual features of the tooth-cutting process, so they do not provide for the production of cylindrical gears with tooth profiles suitable for use in gear transmissions. The studies are being carried out that take into account the actual geometric characteristics of the cutting, shaping part of the teeth of the disk cutter and the kinematic features of the tooth-cutting process, which consist of a periodic, continuous change in the angular speed of rotation of the eccentric machine tool mandrel with a disk tool [544, 545] to ensure the production of gear crowns on cylindrical gears with workable tooth profiles. However, for the practical application of the radial-circular shaping method, with full use of the corresponding characteristics, detailed modeling of the shaping of the profiles of the teeth of cylindrical gears by the side surfaces of the cutting teeth of the disk cutter that form the initial tool surface, is required.

The study aimed to simulate the process of cutting cylindrical gears using the continuous shaping method of tooth profiles with non-profiled disk milling cutters (CSTDC).

Research results. The CSTDC method for cutting cylindrical gears differs from the gear milling process with worm cutters. The CSTDC method is carried out on gear milling machines with similar technological settings as those used for gear milling with worm cutters. A disk cutter is installed with a radial offset of eccentricity e on the tool holder of the gear milling machine, the axis of which coincides with the axis of rotation of the gear milling machine spindle.

The process diagram is shown in Figure 1.

Continuous rotation of the tool holder and the disk cutter, coordinated with the rotation of the cylindrical gear being cut, ensures periodic deepening and exit of the disk cutter from the formed inter-tooth cavity of the resulting gear, creating a profile on the two side surfaces of the cylindrical gear tooth.

The mutually kinematically coordinated rotations of the spindle with the tool holder and the table of the gear milling machine ensure continuous uniform division of the gear wheel blank into the appropriate number of teeth. The used disk milling cutter with cutting teeth of a certain width causes the gear wheel teeth to be cut with a tooth thickness that is less than the required width by an amount approximately equal to twice the width of the principal cutting edge of the disk milling cutter tooth. Neglecting this feature of the gear-cutting process leads to the production of inoperable gears.

This drawback is proposed to be eliminated by changing the law of rotational motion of the disk cutter - by giving the eccentric part of the tool holder together with the disk cutter periodic uneven rotation. For this, an additional device for changing the angular velocity is installed on the tool holder. The input link of this device is connected to the spindle of the gear milling machine, and the output link is connected to the eccentric bushing on which the installed disk cutter is fixed. The angular velocity change device provides a determined slow rotational movement of the disk cutter when entering the inter-tooth cavity of the gear being cut and accelerated rotational movement when the disk cutter exits the inter-tooth cavity. Thanks to this, a disk milling cutter produces cylindrical gear teeth of the required thickness with a profile close to a modified involute profile, known for its enhanced operational characteristics [544, 545].

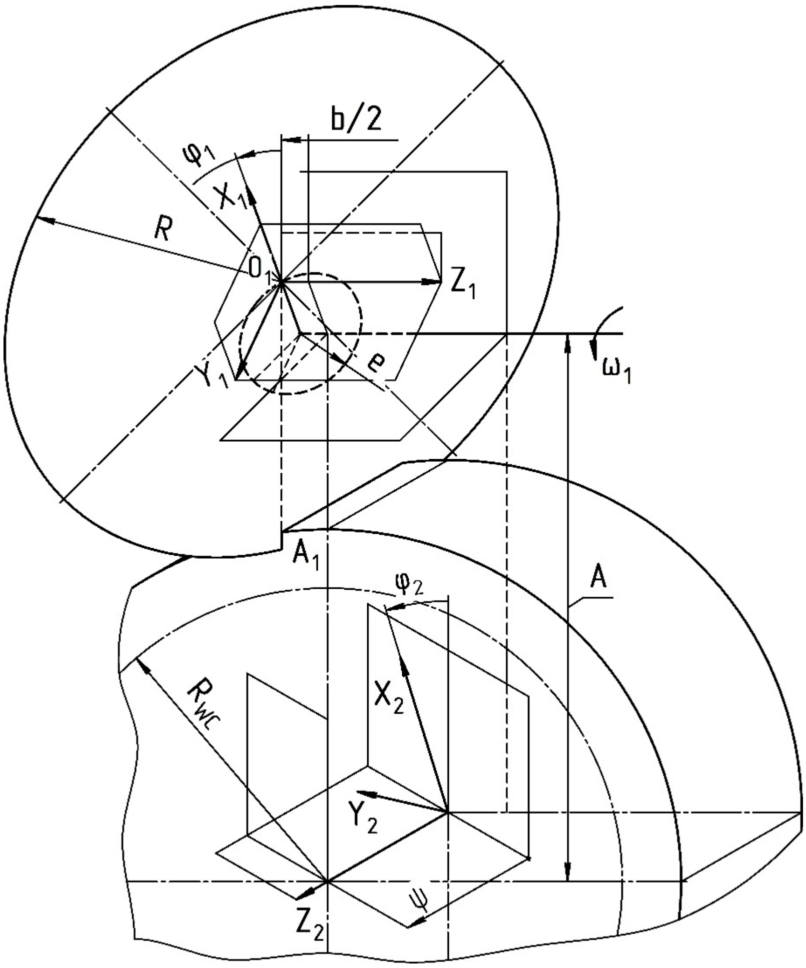


Figure 1. Scheme of continuous shaping of cylindrical gear tooth profiles with a disk milling cutter

These features define a new method of tooth cutting of cylindrical gears - the continuous shaping method of tooth profiles with non-profiled disk milling cutters (CSTDC).

The angular velocity change device, together with the tool holder of the gear milling machine, provides the disk cutter with a rotational motion with a periodically changing angular velocity ω_1. The tool holder receives rotational motion from the spindle of the gear milling machine with a constant angular velocity ω_{01}. The angular velocity ω_{01} of the rotation of the spur gear is related by the relation $\omega_2 = Z \cdot \omega_{01}$, where Z is the number of teeth of the spur gear.

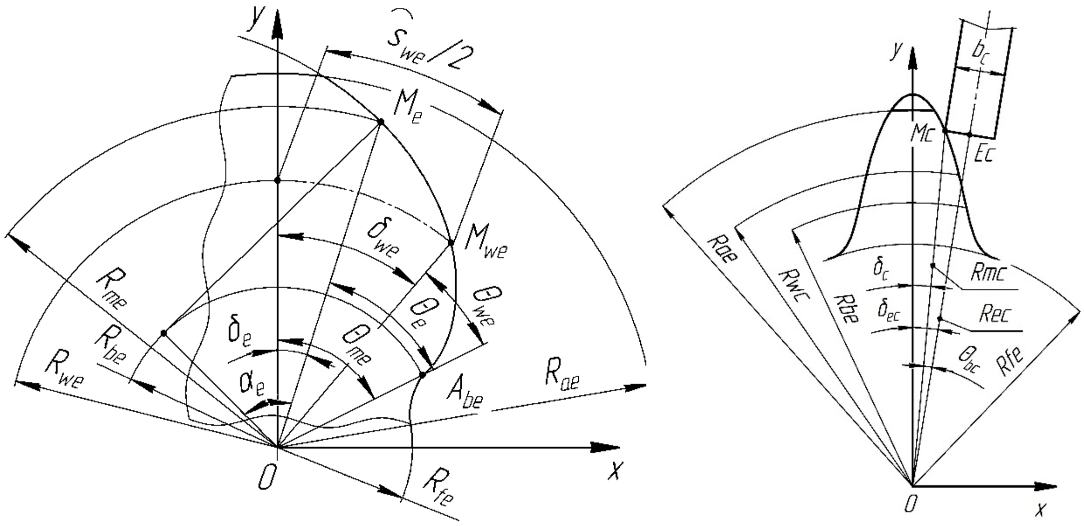
The angular velocity change device consists of one or two pairs of identical cylindrical gears having a similar offset of the tooth crown gears relative to their axes of rotation. In the angular velocity change device, each cylindrical gear has the offset of the tooth crown gear e_r, the number of teeth Z_{01}, the radii of the initial circles R_{01} and the similar centre distance lr in one pair of gears ($l_r = 2R_{01}$). The uneven angle of rotation φ_1 of the output link of the angular velocity change device, which is connected to the eccentric part of the tool holder and the disk cutter, is determined relative to the uniform angle of rotation φ_{01} of the spindle of the gear milling machine by the following dependence:

$$\varphi_1 = 2 \cdot \operatorname{arctg}\left(\left(\frac{l_r - e_r}{l_r + e_r}\right)^k \cdot \operatorname{tg}\frac{\varphi_{01}}{2}\right), \qquad (1)$$

where k is the number of identical pairs of wheels with offset gear rims.

The widespread use of wheels with involute profile teeth in gear transmissions encourages the adoption of the CSTDC method, which is promising for gear cutting to obtain cylindrical gears with a modified involute profile of the teeth. To do this, it is necessary to obtain a ratio for determining the value of the technological parameter - eccentricity (e) of the installation of a disk cutter on the tool holder of a gear milling machine. Modeling of the gear-cutting process with a disk cutter using the CSTDC method is carried out based on the analysis of the parameters of the involute and convexo-concave modified profile of the teeth of the cylindrical gear shown in Figure 2.

The condition of compatibility of profiles is determined by the coincidence of points M_c and M_e , which belong to the convex-concave modified and involute profiles, respectively, which is ensured by the equality of the radius vectors of points M_c and M_e (respectively R_{mc} and R_{me}) and the central angles (respectively δ_c and δ_e): $R_{me} = R_{mc}$ and $\delta_e = \delta_c$.



(a) (b)

Figure 2. Parameters of tooth profiles of cylindrical gears

(involute profile (a), convexo-concave modified profile (b))

The parameters of the convexo-concave modified tooth profile (see Figure 2 (b)) determine the profile by the coordinates of the point M_c of contact of the cutting edge of the disk cutter according to the following dependencies:

$$X_{mc} = \pm R_{mc} \cdot \cos\delta_c ; \qquad Y_{mc} = R_{mc} \cdot \sin\delta_c , \tag{2}$$

where R_{mc} and δ_c are the radius vector and the polar angle of the point M_c, respectively; "±" - the "+" sign determines the profile on the right, and "-" on the left side of the wheel tooth.

The radius vector R_{mc} of the profiling point M_c, the radius vector R_{ec} of the middle of the cutting edge of the disk cutter, and the radius of the initial (pitch) circle R_{wc} are determined using geometric relations according to the following dependencies:

$$R_{mc} = \sqrt{R_{ec}{}^2 + \left(\frac{b_c}{2}\right)^2} , \tag{3}$$

$$R_{ec} = R_{wc} + e \cdot \cos\varphi_1 , \tag{4}$$

$$R_{wc} = \frac{1}{2} \cdot m \cdot Z - 1{,}25 \cdot m + e . \tag{5}$$

where b_c is the width of the cutting edge of the disk cutter; e is the eccentricity of the disk cutter installation on the tool holder; m is the module of the cylindrical gear wheel.

The uneven angle of rotation φ_1 is determined by expression (1).

The central angle of rotation δ_c of the radius vector R_{mc} is determined using the expressions:

$$\delta_c = \delta_{ec} - \theta_{bc} \ ,$$

$$\delta_c = \frac{\varphi_{01}}{Z} - \arcsin\frac{b_c}{2 \cdot R_{mc}} \ , \tag{6}$$

where δ_{ec} and θ_{bc} are respectively the central angles of rotation of the disk cutter and half of the cutting edge of the disk cutter.

Applying dependencies (3) – (6), we obtain the final expression for determining the polar coordinates of points of a convexo-concave modified profile in which the sought, unknown factor is the eccentricity:

$$R_{mc} = \sqrt{\left(\frac{1}{2} \cdot m \cdot Z - 1{,}25 \cdot m + e \cdot (1 + e \cdot cos\,\varphi_1)\right)^2 + \left(\frac{b_c}{2}\right)^2} \ . \tag{7}$$

The characteristics of the involute profile (see Figure 2 (a)) determine the radius-vector R_{me} and polar angle δ_e of the point M_e of the involute profile that is potentially formed by the cutting edge of the tooth of the disk cutter. For the involute profile, the radius-vector R_{me} and polar angle δ_e are set according to the following relations:

$$R_{me} = R_{we} \cdot \frac{\cos\alpha_{we}}{\cos\alpha_e}; \tag{8}$$

$$\delta_e = \theta_{me} - \theta_e, \tag{9}$$

where α_{we} and α_e are the pressure angles at the involute points, respectively, on the pitch circle R_{we} with radius and the considered circle with radius R_{me}; θ_{me} is the angle between the plane of symmetry of the tooth and the beginning of the involute; θ_e is the involute angle at the involute point M_e.

Using the relation for the involute profile, we obtain:

$$\theta_{me} = \theta_{we} + \delta_{we}, \tag{10}$$

$$\theta_{we} = \mathrm{tg}\,\alpha_{we} - \alpha_{we}, \tag{11}$$

$$\theta_{e} = \mathrm{tg}\,\alpha_{e} - \alpha_{e}\ , \tag{12}$$

$$\delta_{we} = \frac{\pi}{2 \cdot Z} \tag{13}$$

where θ_{we} is the involute angle at the involute point on the pitch circle with radius R_{we}; δ_{we} is the central angle between the plane of symmetry of the tooth and the radius-vector of the pitch circle point R_{we}; α_{we} and α_e are the involute pressure angle at a certain involute point and at the involute point on the pitch circle, respectively.

The pressure angle α_{we} at the involute point on the pitch circle R_{we} is equal to the normal profile angle and is for a standard involute profile $\alpha_{we} = 20°$.

The value of the central angle δ_{we} is set taking into account the fact that on the pitch circle the tooth thickness s_{we} and the width of the intertooth cavity e_{we} are equal and depend on the number of teeth of the wheel *Z*, the module and are determined by the value of half the normal pitch $s_{we} = \pi \cdot m / 2$. The pressure angle varying α_e along the involute is determined by expression (8).

Using dependencies (8) – (13) and taking into account $R_{me} = R_{mc}$, we obtain the original equation for determining the unknown radius-vector R_{mc}:

$$\begin{gathered}\left(\mathrm{tg}\,\alpha_{we} - \alpha_{we}\right) - \mathrm{tg}\left(\arccos\left(\frac{R_{we}}{R_{mc}} \cdot \cos\alpha_{we}\right)\right) + \arccos\left(\frac{R_{we}}{R_{mc}} \cdot \cos\alpha_{we}\right) + \\ + \frac{\pi}{2 \cdot Z} - \frac{\varphi_{01}}{Z} + \arcsin\frac{b_c}{2 \cdot R_{mc}} = 0\end{gathered}\ . \tag{14}$$

The determined radius vector R_{mc} derived from the nonlinear equation (14) through the numerical solution is used to calculate the eccentricity *e*, using expression (7).

The final expression for calculating the value of eccentricity *e*, at which the convexo-concave modified profile is closest to the involute profile, has the following form:

$$e = \frac{1}{2} \cdot \frac{-2 \cdot (R_{we} - 1{,}25 \cdot m) + \sqrt{4 \cdot R_{mc}{}^2 - b_c{}^2}}{1 + cos\varphi_1} \tag{15}$$

Obtaining a numerical solution of equation (14) relatively R_{mc} is expedient to simplify by transforming equation (14) into a Taylor series in the vicinity of a point lying on the pitch circle of the gear wheel. The corresponding calculations were performed using the mathematical package of symbolic calculations ”Maple”. For a spur cylindrical gear with parameters m = 10 mm; Z = 18; $\alpha_{we} = 20^0$; disk cutter: $b_c = 5$ mm; angular velocity change device: k = 3, mm, $l_1 = 72$ mm; $e_r = 6$ mm; for the angle of rotation of the spindle of the gear milling machine $\varphi_{01} = \frac{\pi}{2}$ based on equation (14), the Taylor series takes the following form:

$$\begin{gathered}0{,}419540086 - 0{,}004352874829 \cdot R_{mc} - 0{,}000166165366 \cdot (R_{mc} - R_{we})^2 + \\ + 0{,}6587848291 \cdot 10^{-5} \cdot (R_{mc} - R_{we})^3 - 0{,}43732413 \cdot 10^{-6} \cdot (R_{mc} - R_{we})^4 = 0\end{gathered}.$$

Using the previous expression and expression (15), we calculate the value of the radius-vector R_{mc} = 95.416 mm for a point on the convexo-concave modified profile and the value of the eccentricity of the installation of the disk cutter on the tool holder - *e* = 12.22 mm. A comparison of the teeth of a cylindrical gear wheel with convexo-concave modified and involute (standard) profiles is shown in Figure 3. In general, there is a practical coincidence of the profiles.

An important feature of the resulting convex-concave modified profile is that the wheel tooth is obtained with a flank. Flanked involute profile teeth, the production of which in practice is accompanied by significant technological difficulties, increase the smoothness of operation and durability of the cylindrical gear transmission, mainly at a significant wheel rotation frequency. Unlike involute flanked teeth, convexo-concave modified profiles on the teeth of cylindrical wheels are obtained by the CSTDC method in a technologically much simpler way using disk cutters of the general design. In addition, the proposed method for selecting technological and design parameters of tooling makes it possible to obtain teeth with a convex-concave modified profile, satisfying the requirements for the size of the lateral clearance in cylindrical gear transmissions.

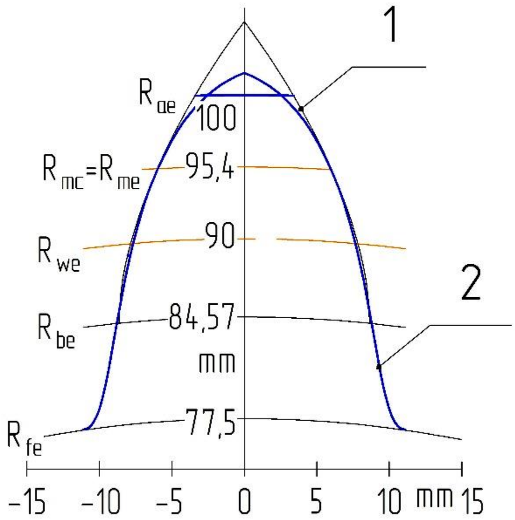


Figure 3. The tooth profile, obtained by continuous shaping with a disk cutter (involute profile (1), convexo-concave profile (2)).

Cutting of cylindrical gears can be carried out on a gear milling machine by the continuous shaping method of tooth profiles with non-profiled disk milling cutters (CSTDC).

Mathematical models have been developed that allow for reasonably establishing technological parameters for obtaining a convexo-concave modified profile of cylindrical gear teeth with improved performance characteristics concerning the smooth operation and contact of wheel teeth in cylindrical gear transmission.