Generation of precessional gear teeth by plastic deformation

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Abstract. The correct choice of the dimensions of the workpiece product is one of the main problems, the solution of which depends on the reduction of the consumption of materials and energy, as well as the quality of the wheels obtained by plastic deformation. Referring to the manufacture of conical wheels with convex-concave profile of the teeth by knurling, the height of the teeth is determined by the condition of the equal volume of metal that moves from the gaps between the teeth to their tip during the plastic deformation by rolling. The use of methods for the manufacture of teeth without chipping will allow the increase of the utilization coefficient of expensive materials.

1. Introduction

Gears are machine parts that occupy an essential place in the operation of various mechanical constructions. The execution of the gears at a high-quality level and at a low cost, puts in front of the specialist multiple problems.

From the design stage, the specialist must take certain measures to achieve a high reliability of the designed gears. Shapes of teeth profiles that can be obtained by plastic deformation [1, 2] for use in precessional multipliers are presented. Starting from the correct choice of materials and dimensions of the workpiece product, the designer must adopt constructive solutions of the gears that can be made in the most economical conditions. Previous research by the author has been presented in [3, 4, 5].

2. Determination of the displacement value of the deformation node in the direction of the axial feed

Based on the computerized model of the toothed wheel plastic deformation device, the working strokes (vertical table feed), the number of revolutions of the main machine tool shaft, were analyzed to ensure the deformation speed prescribed by the technical literature.

Determination of the vertical feed of the table is necessary for the complete teeth formation [3, 4, 6].

Determining the total stroke of the plastic deformation rollers in order to obtain the full height of the teeth requires the determination of the height of the teeth, which is calculated from:

\[ h_{th} = R_{out} \cdot \tan \theta \]  

(1)

where: \( R_{out} \) is the outer conical radius of the blank, mm;

\( \theta \) is the angle of nutation, degrees.

The height increase of the tooth according to the vertical advance of the plastic deformation node, in which the plastic deformation rollers are fixed, was determined according to the relation:
\[
\Delta h_{pc} = s_{pc} \cdot \cos(\delta + \beta + \theta)
\]

where: \(\delta\) is the angle of the conical axoid, degrees;
\(s_{pc}\) is the advance of the plastic deformation node to a precession cycle, mm;
\(\beta\) is angle of conicity of the rollers, degrees.

The value of the stroke of the plastic deformation node in which the plastic deformation rollers are fixed:

\[
s_t = \frac{h_{th}}{\cos(\delta + \beta + \theta)}
\]

According to the literature recommendations for the total teeth profile formation [5], the summary advance was divided into steps, measured by the digital indicator. The results of calculating the penetration advance according to tooth height are presented (see table 1).

### Table 1. The advance depending on the height of the teeth.

| Step No | The angle of nutation \(\theta\), degrees | Angle of the conical axoid \(\delta\), degrees | Angle of conicity of the rollers \(\beta\), degrees | Height of the teeth \(h_i\), mm | The advance, \(s_{pci}\), mm |
|---------|----------------------------------------|------------------------------------------|------------------------------------------|----------------|----------------|
| 1.      |                                        |                                          |                                          | 13.72          | 13.73          |
| 2.      |                                        |                                          |                                          | 14.22          | 14.23          |
| 3.      | 3.0                                    | 0                                        | 3.5                                      | 14.72          | 14.73          |
| 4.      |                                        |                                          |                                          | 15.22          | 15.23          |
| 5.      |                                        |                                          |                                          | 15.52          | 15.53          |

3. **Forces determination for plastic deformation with precession tool**

Knowledge of the forces necessary for the formation of the teeth is an important factor for the calculation of the plastic deformation of toothed wheels. It should be noted that in all of the conceptual developed diagrams the plastic deformation tool performs spherio-spatial motion, which reduces by about 60% the value of the forces required for tooth deformation due to the reduction of the instant contact surface of the tool with the blank. The progressive plastic deformation aims to reduce the deformation pressure by dividing the deformation width into several sectors. The plastic deformation of the teeth with a precession tool and deformation with \(i\) rolls is further examined. In figure 1 (a) the action of the deformation rollers on the blank is replaced by an equivalent roll. The torque transmission (forces) from the main shaft is carried out with arms help \(F_{hi}=f(e)\) figure 1 (b), measured in the planes passing through the application points of the \(F_{hi}\), levers \(L_1\) and \(L_2\): \(R_m \cdot L_1 = F_{hi} \cdot L_2\). The deforming forces acting on the workpiece, when the deformation process is already stabilized, are shown in figure 1 (c). The deformation rolls act with the normal force \(F_n\) and the tangential force \(F_t\), and \(R_m\) is their result.

The normal force, being the sum of the elementary forces relative to the surface unit of the deformation zone, results from the relation: \(F_n = A \cdot P_m\) where \(A\) is the contact surface in the deformation zone, and \(P_m\) is the mean pressure in the deformation zone. From figure 1 (c) results:

![Figure 1. Scheme for determining the applied torque to the main shaft.](image)
\[ R_m = \frac{F_n}{\cos(\beta_1 + \varphi_f)} \]  (4)

The friction \( \varphi_f \) and pressure \( \beta_1 \) angles, with small values, can be approximated: \( R_m = F_n \), resulting in: \( R_m = A P_m \). The average \( P_m \) pressure, in the case of hot deformation, as indicated in the literature, varies within very wide limits: \( P_m = (0.5\ldots9)\tau_r \) in which \( \tau_r \) is the tensile strength of the material of the workpiece subjected to deformation.

The torque \( T \) required to deform the material is determined from the relationship:

\[ T = R_m H = A P_m \frac{d_1}{2} \sin(\beta_1 + \varphi_f) \]  (5)

The torque applied to the crank shaft is determined from the relationships shown in figure 1.

The \( F_{rh} \) force is determined from the relationships:

\[ F_{rh} L_1 = R_m \cos(\beta_1 + \varphi_f) L_2 \]

\[ F_{rh} = \frac{R_m \cos(\beta_1 + \varphi_f) L_2}{L_1} \]  (6)

The torque applied to the crank shaft is determined from the relationships, which from figure 1 (b) results: \( T_h = F_{rh} L_1 \). Replacing the expression for \( F_{rh} \), also \( L_2 = R_m z_2 \) (the average conic length of the manufactured wheel) and \( L_1 = \frac{e}{\tan \theta} \) obtain the relation: \( T_h = R_m \cos(\beta_1 + \varphi_f) R_m z_2 \tan \theta \approx A P_m R_m z_2 \tan \theta \).

In the obtained relationship, \( R_m \) represents the equivalent resultant force, with which it acts on the equivalent of the roll of the semi-fabric teeth.

In fact, thanks to the large number of rollers, which simultaneously participate in the plastic deformation process of the teeth of the blank \((Z_2-1)/2\), the load, which returns to a deformation roll, is smaller.

At the basis of the elaboration and design of the experimental devices of plastic deformation were taken in account the following technical solutions.

In order to simplify the construction of the device (figure 2), a construction that differs from the wheel machining device has been developed in the absence of the mechanism for correcting the profiles of the teeth [1].

![Figure 2. Device construction: (a) measuring the speed of the crankshaft; (b) the plastic deformation node.](image-url)
Also, the device does not have the mechanism of transformation of the movement, which requires the machining of the blank by teeth of the linear profile.

According to the researches carried out, the maximum load, which corresponds to a deformation roll, does not exceed 20-30% from the total load, taking into account the unevenness of the distribution of the deformation force between the rollers simultaneously participating in the plastic deformation process of the teeth, characterized by possible manufacturing errors and deformation of the technological equipment parts [5].

Figure 3 (a) – (d) shows the evolution of the plastic deformation of the teeth of the central wheels of the precessional gear with convex-concave profile of the teeth.

4. Arguing the choice of the teeth profile of the central wheel of the precessional multiplier

In figure 4 there are presented teeth profiles selected from the set of profiles obtained by the authors in order to have some geometric parameters depending on the pre-existing angle: the angle of the conical axoid $\delta = 0 \ldots 30^\circ$; nutation angle $\theta = 1.5^\circ \ldots 3^\circ$; the conicity angle of the rollers $\beta = 4^\circ \ldots 7^\circ$; number of teeth $z_1$ and rollers $z_2$, $z_1 = 10 \ldots 60$; $Z$, mm the height of teeth; $Y$, mm the width at the foot of the teeth; the relationship between the number of central and crown wheels of the satellite, $z_i = z_2 \pm 1$.

The analysis of the forces acting in contact with the teeth of the central wheel and the rollers of the satellite crown showed that the minimization of power losses in the multiplier gear is achieved at high gearing angles (low pressure angles) [7]. At the same time, at low gear angles, self-braking effects occur during the operation of the transmission in multiplication mode [5, 7, 8].

The nutation angle $\theta$ (inclination of the crank) must be as large as possible to ensure a higher load-bearing capacity (a torque applied to the leading element) and, at the same time, as small as possible to ensure minimum height and extended profile of the teeth.
5. Conclusion and future research
The identification of the profiles of the teeth that can be obtained by plastic deformation will allow the establishment of the manufacturing technology still at the design stage. For future research, it is proposed to study more deeply the processes that take place in the plastic deformation with precessional tool of the teeth with convex-concave profile, including at micro- and macro-level, with the prediction of the mechanical properties of the surface layer.

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