Prevention of undercutting of the leg of the tooth of cylindrical helical gears during roughing and finishing gear processing

Damir Safarov* and Alexey Kondrashov

Naberezhnye Chelny institute (branch) of the Kazan (Volga) Federal University, 423812, Naberezhnye Chelny, Mira Ave., 68/19, Russia

* Safarov-dt@mail.ru

Abstract. The article discusses design factors leading to inconsistencies in the diametrical dimensions of the boundary point of the transition curve of the helical wheel. The conditions for the implementation of the graphic run-outs of the gear rack of a worm gear-cutting cutter, ensuring the formation of the active length of the involute wheel profile throughout its length, are formulated. The effect of a change in the design parameters of a helper milling tee on the duration of the interaction of the cutting edges and the diametric dimensions of the boundary points of the transition curve of the helical wheel is shown. Reducing the height of the prominence of the worm cutter leads to an increase in the required length of interaction in the steps of the cutter in the process of forming the active profile of the gear tooth. If the graphic run-in does not take into account the actual length of the interaction between the cutter and the workpiece, then the risk of the undercut of the tooth stem increases with decreasing height of the prominence. A diagram of the possible formation of undercutting of the tooth shaft and recommendations preventing its occurrence as a result of the implementation of graphic two-dimensional helical gears are given.

1. Introduction

Helical gears are often used to convert mechanical energy in the transmission mechanisms of modern cars. In the process of designing gears strive to provide various indicators of kinematic, smooth operation, margin of safety.

An important indicator affecting the smoothness of the transfer is the ratio of the end of the overlap. The value of the coefficient is the ratio of the angles of rotation of the wheel, on which the side surfaces of the gear teeth touch the angular pitch of the gear teeth. To ensure the calculated value of this indicator for a gear, it is necessary for each toothed wheel, which is included in its composition, to ensure the specified length of the active tooth profile. Its length depends on the actual value of the diametrical size of the circle of vertices and the boundary point of the involute at the bottom of the groove.

The diametrical size of the circumference of the peaks is formed in the turning or grinding transitions processing the outer cylindrical surface of the teeth of the cutter. There is no problem with ensuring the diametrical size of the circumference of the vertices, since its size can be controlled by subadapting the tool or grinding wheel in the radial direction to the axis of the gear wheel.
The diametrical size of the boundary points belongs to the lower point of the involute profile and is formed as a result of the rolling process of the milling cutter producing profile and the gear workpiece being machined. The position of the boundary point must be lower than the calculated end point of the involute profile determined by the gear design. Providing the specified diametrical size of the boundary points is technologically more difficult, since the results of the rolling process depend on a larger number of factors: the selected design parameters of the worm milling machine, the profile of the grinding wheel, the setup parameters, the mode of the shaping process during the teeth milling and gear grinding.

2. Theoretical part
Of these factors, the design parameters of the worm cutter are significant. With the wrong choice of its design parameters, all subsequent processes of tooth processing will not be able to ensure the position of the involute profile of the side surface of the gear tooth and the transition curve of the gear cavity.

The end point of the involute profile is formed by a specially made elements of a worm milling cutter - a prominence. This thickening on the top of the tooth of the worm milling cutter is the cutting part of the milling cutter that forms the tooth root profile of the gear wheel and, as a consequence, the position of the boundary point. The final nominal diameter of the boundary point (Figure 1) depends on its shape and parameters.

![Figure 1](image)

**Figure 1.** Forms of the protuberance of the tooth of the worm milling cutter a) straightforward b) radius.

As you can see, the designer of the cutting tool can widely change the shape of the prominence from straight to radius, affecting the shape of the gear basin and the position of the boundary point of the involute profile.

Modern design systems, such as, for example, KISSsoft, allow, depending on the form of a prominence chosen by the designer, to calculate the coordinates of the boundary point position. However, numerical calculations are not illustrative, but the built-in design tools do not give hints on the optimal values of the geometric indices that form the form of the prominence. Therefore, for visualization of numerical calculations by the designers of the cutting tool, the methods of the graphical rolling of the profiles of the teeth of the worm milling cutter are used.

Earlier, before the widespread use of personal computers, in order to calculate the parameters of the tooth of a worm gear-cutting cutter, approved methods were used, designed for “manual” graphic design. Then the same techniques were automated by the most qualified engineers of these services in the form of an auxiliary software product, independently based on the initial data, performing a graphical run-in. Increased speed and accuracy of construction. In the course of a long time, this technique was successfully applied to the design of worm milling cutters.
In the preparation of the production of new gears to achieve maximum strength of the gear on the leg of the tooth, it was necessary to optimize the shape of the prominence within wider boundaries. As a result, after the manufacture of pre-production lots of gears, there appeared unexpected discrepancies between the diametral sizes of the boundary points of the involute profile and their calculated values. Moreover, before this kind of inconsistencies did not occur. In the search for the causes of inconsistencies in the sizes of the lower boundary points, all the main design and technological factors were analyzed. The main design factor is the correctness of calculations of the parameters of the prominence of the current method of graphical rolling. To verify it, an alternative calculation method is needed, the accuracy and calculation method of which is completely certain. Common automation systems for graphic design, such as Compass, Unigraphics NX, Adem, do not offer ready-made and proven solutions for performing graphic rolling in the form of tools embedded in their software products. Take advantage of well-known software products [1, 2] and others authors, are designed to solve various problems [4-7], it is impractical because the authors do not fully disclose their method of construction. Therefore, it was decided to create its own graphical rolling program. As in [1], it is implemented as a subroutine using the shell and functions of a more versatile design system - AutoCAD. For a single milling cutter to ensure the correct graphic rolling it provides two conditions:

- Providing rolling in one revolution, accompanied by a one-step offset cutter, the workpiece is rotated by one angular step.
- Ensuring the required number of positions of the toothed rack at the end of the cutter to complete rolling.

The analysis of the correctness of the fulfillment of the specified conditions by the developed subprogram revealed that the graphical construction of the rack rack cutter used earlier, as in the "manual calculation" method of the worm gear cutters, proceeded from the assumption that the active involute profile is formed only within one step [1].

3. Practical part

If the cutter calculations are made for indicators that are beyond the same cutter step, then an undercut of the tooth leg will appear on the machined wheel. A graphic diagram of the formation of an undercut of a tooth leg that occurs beyond the limits of a single step of a worm milling cutter is shown in Figures 4 a, b. The undercut of the tooth shaft is manifested in a decrease in the length of the active involute tooth profile and an overestimated value of the diameter of the transition curve. Therefore, the designed rolling method must run-in at a length significantly exceeding the tooth pitch of the cutter and take into account any possible interaction of the cutter teeth with the allowance for the gear cavity.

![Figure 2](image_url)

**Figure 2.** Extreme positions of the tooth cutter and equivalent gear, a) with the primary embodiment of the 2D graphical rolling, b) a scheme for the formation of an undercut of the active part of a tooth that occurs beyond the limits of a single step of the mill

Multiple graphical check-ins of the created graphic software for the same gear tooth profile parameters, but with varying prominence parameters from \( h_{(pr \ min)} \) to \( h_{(pr \ max)} \), revealed that the complete formation of the active gear profile can occur as within one step. cutters, and within the next
step. Figure 3 shows an example of the completed graphical breakouts for shaping the cavity of the wheel 2. Figure 3 a) shows the break-in according to the previously applied design method, compared to which the “extended” graphic break-in includes a greater number of positions of the producing rack. Figure 3 c) shows the rolling, combining the position of the rail on the base and elongated break-in. The same figure and tables 1, 2 show the diametrical dimensions of the transition points of the boundary points measured in the graphical editor. To check the graphical rolling data, a numerical check was made of the boundary point values in the KISSsoft gear design system.

![Figure 3](image.png)

**Figure 3.** Results of the graphic rolling of the worm milling tooth when processing the wheel 2 cavity (a form of a prominence in the form of a continuous circle) a) initial break-in, performed by design engineers of the cutting tools design service, c) long break, c) combined rolling-in.

The calculation data and the graphical rolling data differ by no more than 0.1 mm, which is due to the measurement errors of the parameters in the graphics system. For wheel 1 - \( m = 5.85, z = 37, \alpha = 20^\circ, \beta = 17.5^\circ \), the evolvent part of the profile is formed almost within one step (Table 1, Figure 2 a).

For wheel 2, when an externally insignificant change in the initial parameters is \( m = 5.75, z = 34, \alpha = 20^\circ, \beta = 20^\circ \), the full formation of the involute profile for most variants of the prominence occurs beyond the limits of one cutter step (table 2, fig. 2a).
Figure 4. Graphs of contact interaction of the tooth of the cutter with the active profile of the gear wheel, refer to its end step a) wheel 1 (m = 5.85 z = 37 α = 20 °, β = 17.5 °), b) wheel 2 (m = 5.75 z = 34 α = 20 °, β = 20 °).

Table 1. The deviations of the diametral size of the transition point boundary point for wheel 1 (milling step Pt = 19,270, Dl ≤ 217.8 mm.)

| hpr, mm | ρa0, mm | Lmin, mm | Lmax, mm | Lmin/Pt | Lmax/Pt | Dlmax, mm | Dl on 1 step, mm | ΔDl, mm | hpr, mm |
|---------|---------|----------|----------|---------|---------|------------|------------------|--------|--------|
| 1.229   | 0.281   | 14,645   | 20,658   | 0.760   | 1.072   | 216,861    | 216,612          | 0.249  | 1.229  |
| 1.437   | 0.562   | 14,144   | 20,157   | 0.734   | 1.046   | 217,040    | 216,986          | 0.054  | 1.437  |
| 1.644   | 0.843   | 13,643   | 19,656   | 0.708   | 1.020   | 217,218    | 217,218          | 0.000  | 1.644  |
| 1.852   | 1.123   | 12,641   | 19,155   | 0.656   | 0.994   | 217,412    | 217,412          | 0.000  | 1.852  |
| 2.060   | 1.404   | 12,140   | 18,654   | 0.630   | 0.968   | 217,621    | 217,621          | 0.000  | 2.060  |
| 2.268   | 1.685   | 11,639   | 18,153   | 0.604   | 0.942   | 217,831    | 217,831          | 0.000  | 2.268  |
| 2.476   | 1.966   | 11,138   | 17,652   | 0.578   | 0.916   | 218,042    | 218,042          | 0.000  | 2.476  |
| 2.684   | 2.247   | 10,136   | 17,150   | 0.526   | 0.890   | 218,256    | 218,256          | 0.000  | 2.684  |

As can be seen, the combination of the initial parameters of the gear 2, compared with the parameters of the gear 1, resulted in significant deviations in the values of the diameter of the boundary points. With a decrease in the height of the prominence, the error in finding the diametral size of the boundary points of the transition curve increases and amounts to a value of 2.204 mm for the minimum value (Table 2).

At the same time, in the calculation, the zone of the corresponding values of the parameters of the protuberance, shown in Figure 5b, calculated by the previously existing method, turns into an area of erroneous decisions and the occurrence of undercut of the tooth shaft in the treated parts.

Table 2. Deviations of the diametral size of the transition point boundary point for wheel 2 (cutter pitch Pt = 19,2235 Dl ≤ 217,8 mm.)

| hpr, mm | ρa0, mm | Lmin, mm | Lmax, mm | Lmin/Pt | Lmax/Pt | Dlmax, mm | Dl on 1 step, mm | ΔDl, mm | hpr, mm |
|---------|---------|----------|----------|---------|---------|------------|------------------|--------|--------|
| 1.207   | 0.251   | 20,358   | 24,856   | 1.059   | 1.293   | 196,586    | 194,382          | 2.204  | 1.207  |
| 1.393   | 0.502   | 19,858   | 24,606   | 1.033   | 1.280   | 196,725    | 194,601          | 2.124  | 1.393  |
| 1.578   | 0.753   | 19,358   | 24,106   | 1.007   | 1.254   | 196,847    | 194,813          | 2.034  | 1.578  |
| 1.764   | 1.004   | 18,608   | 23,606   | 0.968   | 1.228   | 196,970    | 195,331          | 1.639  | 1.764  |
| 1.950   | 1.256   | 17,109   | 22,306   | 0.924   | 1.202   | 197,093    | 195,786          | 1.307  | 1.950  |
| 2.136   | 1.507   | 16,609   | 22,857   | 0.916   | 1.189   | 197,221    | 196,203          | 1.018  | 2.136  |
| 2.322   | 1.758   | 17,109   | 22,357   | 0.890   | 1.163   | 197,352    | 196,589          | 0.762  | 2.322  |
| 2.508   | 2.009   | 16,359   | 21,857   | 0.851   | 1.137   | 197,486    | 196,947          | 0.539  | 2.508  |
4. Conclusions

The design services of machine-building enterprises independently designing a gear-cutting tool should first test the auxiliary programs for the design of cutting tools. In the design of the protuberance of the worm milling tooth to verify the correctness of the graphic rolling, these parameters are the minimum values of the protuberance $h_\text{p r min}$, with the minimum values of the rounding radius $r_\text{pr min}$, since with these parameters the risk of undercutting the tooth stem is higher than with a more rounded his form. To prevent errors in the calculation, you should perform a graphic run-in at least 1.5 milling cutters.

To improve the effectiveness of the identification of technological and design factors deviations made gears, as well as the adequacy of these design methods should be carried out by a multi-functional team consisting of scientists, design engineers and technologists.

References

[1] Technical guides 37.104.06 -1982 Graphic-analytical method of generating the contour of the teeth of gears Naberezhnie Chelny 10 p.
[2] Skrebnev G G and Anan’ev A S 2014 Load distribution between hob teeth Russian Engineering Research. Vol. 34(11) pp. 680-686
[3] Demidov V V and Tabakov V P 2009 Rational axial shift of gear cutter Russian Engineering Research, Vol. 29(9) pp. 936-939
[4] Smolnikov N Ya, Skrebnev G G, Grigorova O L 2007 Study of the influence of the geometric parameters of the gear and the generating circuit on the laws of the formation of the transition curves of the teeth in the process of gear milling and gear shaping by mathematical modeling (Issledovanie vliyaniya geometricheskih parametrov zubchatogo kolesa i proizvodchashchego kontura na zakonomernosti formirovaniya perekhodnyh krivyh zub’ev v processe zubofrezorovaniya i zubodolbleniya metodom matematicheskogo modelirovaniya) Materials of conference «Advanced technologies in mechanical engineering» (Progressivnye tehnologii v mashinostroenii) Volgograd, VSTU Vol. 3(4) - pp. 86-88
[5] Demidov V V and Guskova E V 2012 Influence of tooth profile in modular hobs on the gear-tooth precision Russian Engineering Research Vol. 32(4). pp. 360-363
[6] Fedorov Yu N, Artamonov V D and Zolotukhina O L 2013 The method of parametric stabilization of the process of teeth formation by the rolling method (Metodika parametricheskoi stabilizacii processa zuboobrazovaniya po metodu obkata) News of TulGU. Technical Science (Izvestiya TulGU. Tekhnicheskie nauki) Vol. 8 pp. 202-108
[7] Khusainov R M and Khaziev R R 2017 Modeling of forming technological errors in processing by gear shaping machine IOP Conference Series: Materials Science and Engineering Vol. 240, No 1, article# 012045