Investigation of the influence of gear milling modes of cylindrical gears on the quality parameters of tooth surfaces

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Summary. The current state of the problem of studying the influence of gear milling modes of cylindrical gears on the quality parameters of the tooth surfaces is considered. Insufficient study of this problem and inconsistency of the available results is shown. The relevance and possible areas of application of this research are shown. The research objects are described (the effect of the cutting speed V and feed S during hobbing of cylindrical gears on the roughness parameter Rz, microhardness Hμ, residual stresses 1 and 2, σ1 and σ2 in the tooth surfaces), the accepted methods of planning experiments and presenting results. The results obtained are presented. It is established that the considered relationships can be modeled with sufficient accuracy by statistical methods and can be described by polynomials of the first or second degree. Shows the nature of the change Ra, Hμ, σ1 and σ2, with changes of V and S. Given are calculated according to Ra, Hμ, σ1 and σ2 from V and S.

1 Status of the issue

The influence of gear milling modes of cylindrical gears on the quality parameters of tooth surfaces has not been sufficiently studied.

Researches by A. A. Matalin, P. E. Dyachenko, P. I. Lizardsyn, E. V. Ryzhov, A. G. Suslov, V. P. Fedorov, N. A. Podosenova, G. A. Deryagin, I. A. Birger, V. A. Kravchenko, and others allowed us to establish the nature of the formation of the main characteristics of surface quality during turning, milling, grinding, and some final methods of diamond-abrasive and finishing-strengthening processing. It was shown, in particular, that the feed has the greatest effect on the cutting forces and the level of deformation hardening (hardening) of the surface of the workpiece. The cutting speed determines to a large extent the temperature in the cutting zone, the duration of the impact of deforming forces on the metal. Therefore, as the cutting speed increases, de-hardening processes may occur, surface hardening of the workpiece, the occurrence of tensile residual stresses, etc. The increase in feed causes an increase in roughness, the degree and depth of the incrustation, compressive residual stresses. The complex nature of the dependence of the roughness on the feed can be explained by the fact that when the latter decreases, the thickness of the cut also decreases. The radius of rounding of the cutting edge is commensurate with the thickness of the cut and the chip formation process in such conditions becomes unstable, resulting in increased friction forces on the back surface and the height of the micro-surfaces. Increasing S increases the unevenness of the cutting forces and the vibration in the cutting zone. This leads to more frequent removal of the growth and an increase in Rz values.

Low-carbon steels (18XГГ, 12XН3А, 25XГГ*, etc. according to ГОСТ 4543-71 (Rus.)) are often used for the manufacture of cylindrical gears. These materials are plastic and prone to build-up. In Fig. 1.a shows the effect of V on Rz for a material that is prone to build-up (curve 1) and for a processed material that is not prone to build-up (curve 2). In areas of low (for steel up to 10 m/min) and high speeds (for steel over 50 m/min), the build-up is reduced and the Rz values are reduced.

The circumferential cutting force – the main component of the resultant metal resistance force to cutting - can be calculated using the formula

\[ P_z = C_p m_1^{1.4} S^{0.95} V^{0.5} t^{1.4} k_{10} \delta = 9.8 \]

where \( C_p \) is the coefficient that takes into account the influence of constant factors on the cutting force (for hobs \( C_p = 15 \)); \( k_{10} \) – coefficient taking into account the number of hob threads (if the number of calls \( z_{10} = 1 \) \( k_{10} = 1 \)); \( k_\delta = 1 \ldots 0.5 \) – coefficient taking into account the hardness of the material of the wheels (for example,
When gear cutting cylindrical gears, as well as when cutting in General, the change in cutting forces affects the main characteristics of the quality of the treated surface. Based on the kinematics of gear cutting with worm cutters, the values of \( S \) and \( t \) are closely related. An increase in \( S \) leads to an increase in \( t \).

Thus, with the specified parameters of the cut wheel (\( z, m \)) and the worm cutter (cutting angles, radius of rounding of the cutting edge, material), the main factors affecting the micro-dimensions of the cut teeth when the worm cutter is used are the cutting modes \( V \) and \( S \) and the hardness \( HB \) of the processed material. However, the study [3] of the influence of \( V \), \( S \), and \( HB \) on the \( R_z \) value of the processed teeth during gear milling with worm cutters showed that the influence of \( S \) on \( R_z \) is small (it increases with the increase in the modulus of the processed teeth), and the influence of \( HB \) is practically absent. At the same time, it is noted in [2] that the feed value is limited by the requirements for roughness and undulation of the tooth surface. These contradictory results indicate the need to clarify the influence of tooth milling modes on the parameter of tooth surface roughness in modern conditions of tooth processing.

When cutting metals under the influence of force and heat processes in the cutting zone, the phenomena of hardening and softening of the metal occur, the microhardness of the treated surface changes and there are residual stresses in the surface layer. When cutting, the plastic deformation causes the surface to tilt, due to which the latter is strengthened and increases microhardness of the treated surface, there are residual stresses in the surface layer and reduced plasticity. Heating the metal during cutting leads to its softening, partial return to its original state. The final state of the surface layer is determined by the ratio of hardening and softening processes that depend on the predominance of force or heat factors in the cutting zone. A certain role in the interaction of these processes can be played by the properties of the metal, characterized, in particular, by its hardness \( HB \). In Fig.2 shows the typical dependence of the microhardness of the surface of \( H_\mu \) on the cutting modes [1].

Residual stresses in the surface layer during cutting occur as a result of the interaction of statically and elastically deformed layers. As shown by our research [4], when tooth milling occurs in the surface of the teeth, tensile stresses of the first kind of the order of
260...430 MPa, depending on the material of the wheels. Studies of the effect of cutting modes of cylindrical gear teeth on residual stresses in the tooth surfaces have not been performed before.

Thus, the main factors that determine the quality characteristics of the surfaces of the teeth of cylindrical gears when they are cut with worm cutters under specified processing conditions (parameters of the gear being processed and the worm cutter) are the cutting modes S and V.

To design the manufacturing processes of cylindrical gears, it is necessary to know the degree of influence of cutting modes on various parameters of their quality. Our analysis of postoperative changes in the quality characteristics of the tooth surfaces when processing cylindrical gears [4] showed that there is a technological inheritance of these characteristics in the main operations of tooth processing. As a result, up to 54% of the dispersion of these characteristics is formed during gear cutting for gears that have passed after gear cutting operations of shewing, chemical and heat treatment, tooth-honing, and tooth-rolling. Knowing the relationship between the quality characteristics of the tooth surfaces and the gear milling modes opens up the possibility of controlling these characteristics, both in gear milling and in finished gears.

Thus, the analysis of the issue status allows us to draw the following conclusions:

1. The influence of cutting modes on the quality parameters of the teeth surfaces of cylindrical gears of medium modules (m=2.5-5.0 mm) should take place. However, these relationships have not been studied enough and the findings are contradictory.

2. Knowledge of these relationships will improve the quality of the design of technological processes for manufacturing cylindrical gears, will open up opportunities for managing the quality of gears by selecting rational values of gear milling modes.

3. The problem of studying the influence of gear milling modes of cylindrical gears of medium modules in modern production conditions on the quality parameters of the tooth surfaces is relevant.

### 2 Research method

The study was carried out in the conditions of the Minsk gear plant on a gear milling machine mod.5B312 when processing gears (m=3-5 mm,) made of 25XIT, 40X, 20XH3A steel, which are typical for auto-tractor transmission gears.

First we performed a study of the form of correlation dependencies of the considered parameters of the quality of gears on the modes of gear milling according to the scheme a complete factor experiment (CFE) with the addition of 5 experiments in the center of the plan. The experiment planning matrix used is shown in table 1.

The analysis of the obtained regression lines allowed us to assume that the relationships of Ra with V and S can be considered linear, and H, σ₁ and σ₂ with V and S – nonlinear. Therefore, in the future, more in-depth studies of these relationships for linear dependence were performed according to the PFE scheme (the first 4 experiments in table 1), and for nonlinear dependencies - according to the scheme of rotatable central composition planning (RCCP), the matrix of which is shown in table 2.

### Table 1. Matrix of the experiment in the preliminary study of the relationship between the quality parameters of the gear tooth surfaces and the gear milling modes.

| Number experience's | Factors | The results of the parallel experiments |
|---------------------|---------|---------------------------------------|
|                     | X₁      | X₂                                   | Y₁₁ | Y₁₂ | Y₁₃ |
| 1.                  | -1      | -1                                   | Y₁₁ | Y₁₂ | Y₁₃ |
| 2.                  | +1      | -1                                   | Y₂₁ | Y₂₂ | Y₂₃ |
| 3.                  | -1      | +1                                   | Y₃₁ | Y₃₂ | Y₃₃ |
| 4.                  | +1      | +1                                   | Y₄₁ | Y₄₂ | Y₄₃ |
| 5.                  | 0       | -1                                   | Y₅₁ | Y₅₂ | Y₅₃ |
| 6.                  | -1      | 0                                    | Y₆₁ | Y₆₂ | Y₆₃ |
| 7.                  | +1      | 0                                    | Y₇₁ | Y₇₂ | Y₇₃ |
| 8.                  | 0       | +1                                   | Y₈₁ | Y₈₂ | Y₈₃ |
| 9.                  | 0       | 0                                    | Y₉₁ | Y₉₂ | Y₉₃ |

X₁ – cutting speed V, m / min
X₂ – feed S, mm / min
(-1) – lower level of X₁ and X₂ factors
(+1) – upper level of X₁ and X₂ factors
(0) – average level of X₁ and X₂ factors
The first degree of the form its approximation was performed using a polynomial of lower level.

Upper

The range of variation in basic level

of gear cutting equipment. The accepted intervals for the tooth in the zone of the pitch circle. The average value of 3 measurements was taken into account for each tooth. Measurements \( \sigma_1 \) and \( \sigma_2 \) were performed by x-ray method.

The choice of intervals for changing the modes of gear cutting of cylindrical gears was made by us taking into account the recommendations of the technical literature [2-5], production experience and capabilities of gear cutting equipment. The accepted intervals for changing the tooth milling modes in the performed studies are shown in table 3.

| Experiment system | Number experience's | \( X_1 \) | \( X_2 \) | \( \Delta X_1 \) | \( \Delta X_2 \) |
|-------------------|---------------------|----------|----------|----------------|----------------|
| Full factorial experiment \( (N_1) \) | 1. | -1 | -1 | +1 | +1 |
| | 2. | +1 | -1 | -1 | +1 |
| | 3. | -1 | +1 | -1 | +1 |
| | 4. | +1 | +1 | +1 | +1 |
| Experiments in «star points» \( (N_2) \) | 5. | +1.41 | 0 | 0 | 2.0 |
| | 6. | -1.41 | 0 | 0 | 2.0 |
| | 7. | 0 | +1.41 | 0 | 0 |
| | 8. | 0 | -1.41 | 0 | 0 |
| Experiences in the centre plan's \( (N_0) \) | 9. | 0 | 0 | 0 | 0 |
| | 10. | 0 | 0 | 0 | 0 |
| | 11. | 0 | 0 | 0 | 0 |
| | 12. | 0 | 0 | 0 | 0 |
| | 13. | 0 | 0 | 0 | 0 |

The results of the parallel experiments

| \( Y_{i1} \) | \( Y_{i2} \) | \( Y_{i3} \) |
|-------------|-------------|-------------|
| \( Y_{11} \) | \( Y_{12} \) | \( Y_{13} \) |
| \( Y_{21} \) | \( Y_{22} \) | \( Y_{23} \) |
| \( Y_{31} \) | \( Y_{32} \) | \( Y_{33} \) |
| \( Y_{41} \) | \( Y_{42} \) | \( Y_{43} \) |



Table 2. RCKP matrix of the experiment.

In the study of nonlinear dependencies \( H_y = f(V, S) \), \( \sigma_1 = f(V, S) \), \( \sigma_2 = f(V, S) \) their approximation was performed using a second-degree polynomial of the form

\[
Ra = b_0 + b_1V + b_2S
\]

(1)

The analysis of the experimental data obtained, in addition to calculating the coefficients of equations (1) and (2), also included an assessment of the adequacy of the obtained dependencies, the significance of the coefficients of these equations, and the degree of influence of a particular cutting mode parameter on the considered parameters of the gear tooth surface quality. The last estimation was performed using the influence coefficients calculated according to the table 3.

When studying the linear dependence \( Ra = f(V, S) \), its approximation was performed using a polynomial of the first degree of the form

\[
Ra = b_0 + b_1V + b_2S
\]

(1)

| Characteristics of the experiment plan | \( X_1 \) (V, m/min) | \( X_2 \) (S, mm/min) |
|-------------------------------------|---------------------|---------------------|
| Basic level                        | 32.8                | 6.25                |
| The range of variation in           | 7.6                 | 3.75                |
| Upper level                        | 40.4                | 10.0                |
| Lower level                        | 25.2                | 2.5                 |

Figures 3-6 show the empirical relationships we obtained \( Ra \), \( H_y, \sigma_1 \) and \( \sigma_2 \) from the cutting speed V and feed S, and in table 4 - results of calculations of coefficients of regression equations describing the considered relationships, influence coefficients, and model adequacy indicators for \( y_2 \) (Fischer's criterion F).
and the average relative error of the coupling equation \( e_{av} \).

Fig.3. Empirical dependence \( R_a = f(V) \) (a) and \( R_a = f(S) \) (b) (25hgt steel).

Fig.4. Empirical dependence, \( H_b = f(V) \) (a) and \( H_b = f(S) \) (b) (40X steel).

Fig.5. Empirical dependence \( \sigma_f = f(V) \) (a) and \( \sigma_f = f(S) \) (b) (40x steel).
4 Conclusions

1. Between the surface quality parameters of cylindrical gear teeth (roughness parameter \( R_a \), microns, microhardness \( H_m \), MPa, residual stresses of the first and second kinds \( \sigma_1 \) and \( \sigma_2 \), MPa) there are stable relationships between the modes of gear milling with worm cutters (cutting speed \( V \), m/min and feed \( S \), mm/min), which can be described by polynomial models using experimental planning methods.

2. The calculations confirmed the reliability of the coefficients of the regression equations found using these methods, and the adequacy of these equations (for the obtained equations, the conditions are met \( F < F_{cr} \), \( F_{a}= F_{1,0.05}=7.71 \) и \( e_{av}<30\% \).

3. Dependence \( R_a = f(V,S) \) in the best degree can be described by a polynomial of the first degree, the dependence \( H_m = f(V,S) \), \( \sigma_1 = f(V,S) \), \( \sigma_2 = f(V,S) \) – a polynomial of the second degree. Although to describe the dependency \( H_m = f(V,S) \) with sufficient accuracy \( (e_{av}=8.7-26.5\%) \) a polynomial of the first degree can also be used.

4. The growth of \( V \) causes an increase in \( R_a \) and decrease \( H_m \), \( \sigma_2 \). When increasing \( V \) to about 32 m / min, there is an increase in \( \sigma_1 \), if you increase \( V \) further, it decreases \( \sigma_1 \). Moreover, at 37 m / min<\( V <26 \) m / min, compressive residual stresses occur in the tooth surface, which increases the life of the gears. In the range \( V=26-37 \) m/min, tensile residual stresses are created in the tooth surface during gear milling with a worm cutter. Thus, the range of 37 m / min<\( V <26 \) m / min can be recommended for gear milling of cylindrical gears of medium modules (\( m=3.0-6.5 \) mm).
**Table 4.** Experimental relationships between gear milling modes V and S and the main characteristics of the tooth surface quality (Ra, Hμ, σ₁, σ₂).

| Quality characteristics surfaces teeth | Gear steel grade | Type of dependence of the tooth surface quality parameter on the tooth milling modes | Fisher Criterion F | Average relative error of the coupling equation $\epsilon_{av}$ |
|--------------------------------------|------------------|---------------------------------------------------------------------------------|------------------|--------------------------|
| Roughness parameter Ra, microns      | 40X              | $y_1 = 3.8 + 0.92X_1 + 2.2X_2$                                                 | 1.7              | 5.2                      |
|                                      | 25XIT            | $y_1 = 6.3 + 0.93X_1 + 2.12X_2$                                                | 2.2              | 14.7                     |
|                                      | 20XH3A           | $y_1 = 3.8 + 1.7X_1 + 0.92X_2$                                                 | 3.5              | 26.5                     |
| Microhardness Hμ, MPa                | 40X              | $y_1 = 2021 - 73.6X_1 + 82.4X_2 - 23.7X_1X_2 + 186X_1^2 + 280X_2^2$             | 2.4              | 4.7                      |
|                                      | 25XIT            | $y_1 = 2217.2 - 32.8X_1 + 97X_2 + 9.8X_1X_2 + 4.7X_1^2 - 64.5X_2^2$            | 2.6              | 5.7                      |
|                                      | 20XH3A           | $y_1 = 2007 - 32X_1 + 95X_2 + 12X_1X_2 + 5.3X_1^2 - 79X_2^2$                   | 3.2              | 10.7                     |
| Residual stresses of the first kind σ₁, MPa | 40X | $y_1 = 442 - 145.1X_1 + 122.5X_2 + 122.1X_1X_2 - 273.7X_1^2 + 120X_2^2$       | 1.8              | 6.7                      |
|                                      | 25XIT            | $y_1 = 582 - 184.5X_1 + 160X_2 + 126X_1X_2 - 286X_1^2 - 484X_2^2$              | 3.7              | 11.6                     |
|                                      | 20XH3A           | $y_1 = 565 - 196.6X_1 + 155X_2 + 132X_1X_2 - 275X_1^2 - 490X_2^2$             | 2.6              | 8.6                      |
| Residual stresses of the second kind σ₂, MPa | 40X | $y_1 = 429.2 - 18X_1 + 17.9X_2 - 5.0X_1X_2 + 27.7X_1^2 + 16.6X_2^2$            | 2.3              | 7.3                      |
|                                      | 25XIT            | $y_1 = 156.4 - 17.8X_1 + 17.7X_2 - 5.2X_1X_2 + 54.4X_1^2 + 41.8X_2^2$         | 3.4              | 9.5                      |
|                                      | 20XH3A           | $y_1 = 263.4 - 21.4X_1 + 16.8X_2 + 20.5X_1X_2 + 6.7X_1^2 - 4.8X_2^2$          | 4.3              | 12.8                     |
5. An increase in S causes an increase in $Ra, H_\mu, \sigma_2$, but it leads to a decrease in values $\sigma_1$.

6. The S feed has a 2.5-14 times greater effect on $Ra, H_\mu, \sigma_1$, than the cutting speed V, but about 1.8 times less influence than the influence of V on $\sigma_2$. This indicates that parameter management is much more efficient $Ra, H_\mu, \sigma_1$ in gear milling by changing S than changing V.

7. The proposed research methods and the found dependencies can be used to select the modes of gear milling of cylindrical gears with worm cutters that provide the required values of the quality characteristics of the tooth surfaces $Ra, H_\mu, \sigma_1, \sigma_2$, as well as in the design of technological processes for manufacturing cylindrical gears.

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