Theoretical Analysis of Conditions for Improving Gear Grinding Accuracy and Productivity

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Abstract. The aim of this study is a theoretical substantiation of the possibilities for increasing accuracy and productivity in gear grinding and determining the optimal machining conditions based on the reduction of elastic displacements arising in the technological system. The expediency of gear grinding using the profile copy method is shown based on a theoretical analysis of the conditions for increasing the accuracy and productivity of gear grinding operations. Compared to the traditional milling, this method has more significant technological capabilities in terms of improving the accuracy and productivity of machining. This machining effect appears while implementing the dead-stop grinding, which provides a significant reduction in elastic displacements that occur in the technological system due to the uneven removed stock. In this case, the main part of stock removal is carried out in terms of high-performance deep grinding. For the implementation of gear grinding using the profile copy method, an analytical ratio has been obtained to determine the lateral feed elastic displacement that occurs after each wheel pass. Using this ratio allows achieving high machining productivity with the required accuracy. It has also been found out that it is possible to increase the machining accuracy and productivity during milling by increasing the refinement of the wheel pass by reducing the conditional cutting stress. This can be achieved by using high porosity grinding wheels, providing a decrease in the friction intensity in the cutting zone due to their high cutting ability.

Keywords: Abrasive wheel · Dead-stop grinding scheme · Elastic displacement

V. Ivanov et al. (Eds.): DSMIE 2020, LNME, pp. 305–314, 2020.
https://doi.org/10.1007/978-3-030-50794-7_30

1 Introduction

Gear grinding is the final operation of the gear teeth machining, providing high accuracy and quality of the finished surfaces. Traditionally, gear grinding operations are carried out by the milling method in milling cutters. Using high porosity abrasive wheels can significantly reduce the power and thermal tension of gear grinding; eliminate the formation of thermal damage, microcracks and other temperature defects on the finished surfaces. However, the machining productivity is relatively low, and in practice that leads to forcing cutting conditions, and as a result, decreasing the accuracy and quality of the machined surfaces. Therefore, instead of milling, gear grinding technology using the profile copy method is being increasingly used, implementing a scheme of high-performance deep grinding. In this case, the stock removal is carried out in one or several passes of the grinding wheel, which reduces the additional machining time for a rotary table in comparison with gear grinding in milling cutters. The main disadvantage of this gear grinding technology is the relatively low machining accuracy, which is mainly due to the uneven removed stock on both sides of the grinding wheel. The reason for this is the occurrence of thermoelastic deformations of the teeth during its thermal or/and chemical treatment and improper wheel installation in the machined gear wheel space. As a result, elastic displacements occur in the technological system, causing machining errors. In addition, uneven removed stock leads to increased thermal tension during grinding, as well as to the occurrence of temperature defects on the machined surfaces which requires a reduction in machining productivity. Regarding this, it is necessary to theoretically substantiate the conditions for increasing the efficiency of the gear grinding technology using the profile copy method.

2 Literature Review

The studies of gear grinding rules by the profile copy method have been paid less attention than the milling method in the scientific and technical literature [1, 2]. Meanwhile, the published works [3–5] revealed significant technological capabilities of this progressive gear grinding technology, which is implemented most fully on modern CNC gear grinding machines. In the work [6] we can see that specific example show the feasibility of measuring the accuracy parameters of machined gears using a coordinate measuring machine, which provides more accurate adjustment of the gear grinding machine and thereby reduces processing errors. However, there is no theoretical analysis of the conditions for increasing the accuracy and machining parameters in these works, which does not allow to provide a scientifically substantiated selection of rational gear grinding parameters. There are no theoretical solutions defining ways to increase the accuracy and processing parameters to a level that exceeds the level achieved by gear grinding using the rolling method.

Particularly valuable is the work [7] devoted to gear hobbling at finishing operations; however, it does not provide a comparison of this technology with modern gear grinding technologies.

The work [8] is devoted to the analytical determination of the cutting force during grinding and turbine blade machining. Nevertheless, it gives no calculation and analysis of elastic displacements that occur in the technological system under the influence of cutting forces, which, as a rule, predetermine the parameters of machining accuracy during gear grinding. The same conclusion can be made regarding the works [9, 10] devoted to the experimental determination of the cutting force during grinding and turbine blade machining.

It should be outlined that much less attention is paid to the studies of the power tension parameters during gear grinding than to the studies of the heat tension parameters and the search for ways to reduce the cutting temperature [11–13]. This is since gear grinding needs increased contact area of the wheel with the workpiece and it features increased cutting temperature. As a result, thermal damage and microcracks formation tend to increase in number on the machined surfaces, reducing the quality of machining.

3 Research Methodology

The analysis of literature showed no analytical ratio for determining the accuracy parameters of gear grinding connected to the occurrence of elastic displacements in the technological system. Thus, the distinctive features of the formation of machining errors are not substantiated theoretically during gear grinding using the profile copy and milling methods. This does not allow to reveal the potential technological capabilities of these gear grinding methods and theoretically determine the optimal machining conditions that provide a significant increase in accuracy and productivity. Therefore, our task is to mathematically describe the patterns of elastic displacements formation that occurs in the technological system during gear grinding using the profile copy and milling methods. It is necessary to establish the analytical relationship between the magnitude of the elastic displacement and the main processing time, and determine the most productive gear grinding method, taking into account the limitations on processing accuracy further. Also, there is a need to justify the optimal processing conditions on this basis, including the parameters of the grinding mode and the number of passes of the wheel. In this case, the processing accuracy is determined by the amount of elastic displacement: when it is smaller, then the processing accuracy is higher.

In work [14], a theoretical approach to optimizing gear grinding parameters by the profile copy method was proposed. Based on it, the optimal machining route is determined, consisting of 4 wheel passes when removing stock $P = 0.4$ mm per side. The first pass is supposed to remove the main part of the stock (0.37 mm), and subsequent passes remove 0.01 mm per each pass. It was found out experimentally that such a route provides high machining productivity, but reduces machining accuracy. This takes place because with each subsequent wheel pass, due to a decrease in elastic displacements, the width of the space between the machined teeth increases, exceeding the permissible value. The gear space is broken down, which reduces machining accuracy. Under these conditions, the resulting machining errors can be eliminated by feeding the grinding wheel after each pass to the appropriate value.

To determine this feed value, it is advisable to study initially the changing nature in the elastic displacement y that occurs in the technological system in multi-pass grinding (for n passes of the grinding wheel) according to the dead-stop grinding scheme based on analytical dependencies [15]: $y = P_y/c = P_z/(c \cdot K)$, where c is a given rigidity of the technological system, N/m; $K = P_z/P_y$ is a grinding coefficient; P_z, P_y is tangential and radial components of the cutting force, N.

Reporting in terms of $P_z = \sigma \cdot F$, the relationship between the elastic displacements y_n and y_{n-1} arising on the n-th and ($n-1$)-th passes of the grinding wheel is established by the formula (1):

$$y_n = \frac{y_{n-1}}{\varepsilon} = \frac{t}{\varepsilon^n}, \tag{1}$$

where σ is the conditional cutting stress, N/m^2; $F = Q/V_c$ is the total instantaneous cross-sectional area of a slice of ganged grains of a grinding wheel, m^2; $Q = B_1 \cdot t \cdot V_{det}$ is the processing performance, m^3/s; B_1 is the grinding width, m; t is the grinding depth, m; V_c, V_{det} is the speed of a wheel and a workpiece, m/s; $\varepsilon = \dfrac{c \cdot K \cdot V_c}{\sigma \cdot B_1 \cdot V_{det}}$ is the refinement of a wheel pass.

The total refinement of ε_0 is equal to:

$$\varepsilon_0 = \frac{t}{y_n} = \varepsilon^n. \tag{2}$$

The larger the values of t and ε, the smaller the number of passes of the wheel n, the given value y_n can be achieved, which determines the machining error. Nevertheless, the main condition for increasing the refinement in the wheel pass ε is a decrease in the workpiece speed V_{det}. However, this leads to an increase in the main machining time τ. Therefore, it is necessary to determine the optimal values of n and V_{det} at which the main machining time τ takes the smallest value. Representing $\tau = n \cdot L/V_{det}$ and resolving the ratio $\varepsilon = \dfrac{c \cdot K \cdot V_c}{\sigma \cdot B_1 \cdot V_{\det}}$ to the workpiece speed Vdet, we obtain:

$$\tau = \frac{n \cdot L \cdot \sigma \cdot B_1}{c \cdot K \cdot V_c} \cdot \sqrt[n]{\varepsilon_0}, \tag{3}$$

where L is the stroke length of the machine table, m.

It follows according to the ratio (3) that there is an extremum of the function τ on n. Subordinating the ratio (3) to the necessary condition for the extremum ($\tau'_n = 0$), we obtained $\varepsilon_0 = e^n$, $n = ln\, \varepsilon_0$, respectively. The second derivative τ''_n at the extremum of the function τ is positive. Therefore, the minimum of the function τ is realized, at which the refinement of the wheel pass ε is equal to the number $e \approx 2.72$.

The optimal workpiece speed V_{det} is determined by the ratio as follows:

$$V_{det} = \frac{c \cdot K \cdot V_c}{\sigma \cdot B_1 \cdot e}. \tag{4}$$

It is possible to increase the workpiece speed V_{det} and, accordingly, reduce the main machining time τ by decreasing the parameters σ, B_1 and increasing *c, K,* V_c. This is achieved mainly when using high porosity, impregnated and intermittent grinding wheels [15–19], featuring high cutting ability and providing a decrease in the friction intensity in the cutting zone.

It should be outlined that the patterns of change in the elastic displacement that occur under the conditions of an optimal dead-stop grinding scheme ($\varepsilon = e$) are described by an analytical ratio: $y_n = t \cdot e^{-n} = t \cdot e^{-\frac{V_{\det}}{L} \cdot \tau}$.

Therefore, over the machining time τ, the value of y_n decreases exponentially, which corresponds to the known experimental data [15]. Thus, the dead-stop grinding scheme, due to the presence of an elastic system of the grinding machine, automatically implements the optimal grinding cycle with a refinement of $\varepsilon = e \approx 2.72$. This explains the high efficiency of applying the dead-stop grinding scheme in grinding to solve practical problems of ensuring high accuracy and machining productivity.

The drawn theoretical solutions were used to justify the technological possibilities of increasing accuracy and productivity during gear grinding, as well as when choosing the most productive gear grinding method and determining optimal processing conditions.

4 Results

When gear grinding using the profile copy method, the ratio for determining the amount of elastic displacement for various grinding wheel passes is as follows:

$$y_n = \frac{\Delta_0}{\varepsilon^n}, \tag{5}$$

where Δ_0 is the displacement of the cone wheel axis relative to the gear space axis, m; $\varepsilon = \frac{c \cdot K \cdot V_c}{2 \cdot \sigma \cdot B \cdot \cos\frac{\alpha}{2} \cdot S_0}$ is the refinement of a wheel pass; B_1 is grinding width, m; α is the angle at the apex of the cone wheel; S_0 is the longitudinal feed rate made by the grinding wheel along the tooth being machined, m/s.

The optimal longitudinal feed rate S_0 is determined by:

$$S_0 = \frac{c \cdot K \cdot V_c}{2 \cdot \sigma \cdot B \cdot cos\frac{\alpha}{2} \cdot e} \tag{6}$$

In this case, as with grinding according to the dead-stop grinding scheme, the optimal refinement value is $\varepsilon = e \approx 2.72$. Therefore, the technology of gear grinding using the profile copy method allows implementing the dead-stop grinding scheme, which is most effective from the viewpoint of ensuring high accuracy machining. In this instance, increasing the longitudinal feed rate S_0, according to the ratio (6), and reducing the main machining time τ is possible due to decreasing σ, B, α and increasing c, K, V_c.

To achieve the specified machining accuracy by eliminating the breakdown of the gear wheel space, it is necessary to feed the grinding wheel S_1 after each double pass by a certain value $S_{1.n}$ (Fig. 1).

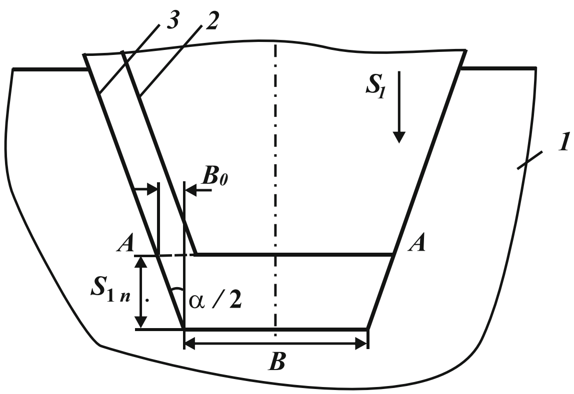

Fig. 1. The calculation scheme of gear grinding parameters using the profile copy method: 1 – gear; 2, 3 – grinding wheel positions at $(n-1)$ and n passes.

When calculating it, it is necessary to take into account the elastic displacement y_{n-1} that occurs in the technological system at the previous pass of the grinding wheel (in section A–A, see Fig. 1):

$$B + y_{n-1} = B + 2 \cdot B_0, \tag{7}$$

where $B_0 = S_{1.n}/tg(\alpha/2)$ is the width of the grinding wheel cone portion at section level A–A, m; B is the width of the wheel's peripheral part, m.

We get as follows:

$$y_{n-1} = \frac{2 \cdot S_{1.n}}{tg\frac{\alpha}{2}}. \tag{8}$$

According to the ratio (8), it follows that the transverse feed $S_{1.n}$ is less than the elastic displacement y_{n-1}, since $B_0 = S_{1.n}/tg(\alpha/2)$. Therefore, in grinding, it is necessary to finely adjust the transverse feed $S_{1.n}$ at each double pass of the grinding wheel, since it will vary within a few microns at the given machining error, for example, 10 μm. Failing to follow this condition will not ensure the required machining accuracy. As a result, there will be a breakdown of the gear wheel machined space, which is observed when using the gear grinding technology using the profile copy method.

When using gear grinding technology by the milling method, the stock on each side of the tooth being machined is removed separately by the end of the cup wheel according to the rigid multi-pass grinding scheme. So, the patterns of the elastic displacements formation that occur in the technological system by wheel passes are described as follows:

$$y_n = \frac{t}{\varepsilon} + \frac{t}{\varepsilon^2} + \cdots + \frac{t}{\varepsilon^n} = \frac{SR}{n} \cdot \frac{(1 - \varepsilon^{-n})}{(\varepsilon - 1)}, \tag{9}$$

where $t = SR/n$ – is the grinding depth, m; SR – is the stock removed, m; $\varepsilon = \dfrac{c \cdot K \cdot V_c}{\sigma \cdot B_1 \cdot S_0}$ is the refinement of a wheel pass.

With an increase in the number of wheels passes n, the value of the elastic displacement y_n increases according to the law of geometric progression. Therefore, to ensure the given machining accuracy, it is necessary to make additional dead-stop wheel passes, which reduces productivity. From this viewpoint, the use of gear grinding using the profile copy method is more effective, because after several wheels pass, a dead-stop grinding scheme is implemented that allows maximum productivity with the given machining accuracy.

Based on the ratio (9), the elastic displacement change nature follows a more complex pattern than when grinding using the dead-stop grinding scheme, which is realized under gear grinding using the profile copy method, where $\varepsilon_0 = \varepsilon^n = e^n$. The elastic displacement y_n can be reduced by increasing n and ε values. However, the increase in n decreases machining productivity. The increase in the refinement of a wheel pass ε by reducing the longitudinal feed rate S_0 also reduces machining productivity. Therefore, the main way to reduce y_n is to increase the refinement of a wheel pass ε by reducing the σ/K ratio and increasing the parameters c and V_c, which do not affect the machining productivity directly. For the practical implementation of these conditions, it is advisable to use grinding wheels with high cutting ability, as well as effective grinding methods.

It should be emphasized that when gear grinding using the milling method, i.e. when using multi-pass grinding, the grinding depth t has to be reduced and the longitudinal feed rate S_0 has to be increased. This leads to a decrease in the refinement ε, however, it is not so efficient for reducing the elastic displacement y_n and machining errors.

When gear grinding according to the profile copy method which implements the deep grinding conditions, it is, on the contrary, necessary to increase the grinding depth t and reduce the longitudinal feed rate S_0. This automatically leads to an increase in the refinement of a wheel pass ε, to a decrease in the elastic displacement y_n and machining errors. Therefore, it is more efficient to use gear grinding by the profile copy method, which provides increased accuracy and machining productivity.

The calculated values of the ratio y_n/SR are represented in Tables 1, 2, based on the ratio (9) and the ratio $\varepsilon_0 = \varepsilon^n$ (for gear grinding by the profile copy method). It is shown that the values y_n/SR (Table 2) are much less than the similar values given in Table 1.

Table 1. The calculated values of the ratio y_n/SR.

ε	n			
	2	3	4	5
1.5	0.555	0.490	0.400	0.347
2	0.375	0.292	0.234	0.193
3	0.222	0.160	0.123	0.100
4	0.156	0.109	0.083	0.066
5	0.120	0.083	0.062	0.050
6	0.097	0.066	0.050	0.040
7	0.081	0.055	0.041	0.033
8	0.070	0.047	0.036	0.029
9	0.062	0.042	0.031	0.025

Table 2. The calculated values of the ratio y_n/SR.

ε	n			
	2	3	4	5
1.5	0.44400	0.29600	0.19800	0.13200
2	0.25000	0.12500	0.06250	0.03100
3	0.11100	0.03700	0.01230	0.00410
4	0.06250	0.01560	0.03900	0.00098
5	0.04000	0.00800	0.00160	0.00032

So, when gear grinding according to the method of profile copying with $n = 5$ and $\varepsilon = \mathrm{e} \approx 3$ (see Table 2), the ratio $y_n/SR = 0.0041$, and when gear grinding is done using the rolling method for the same values of n and ε, the ratio $y_n/SR = 0.1$, i.e. it is 24.4 times less. Therefore, the required machining accuracy in gear grinding using the profile copy method can be ensured at lower n and ε values, which allows increasing machining productivity.

The experimental studies of gear grinding, carried out at PJSC "*Svet Shakhtyora*" using the profile copy and milling methods confirmed the theoretical solutions obtained. It has been found out that gear grinding using the profile copy method is more productive; it allows increasing the productivity up to 5 times while ensuring a given machining accuracy. There is no thermal damage or microcracks on the finished surfaces, and it improves the machining quality. Gear grinding was performed using a high porosity abrasive wheel TIESP 400 × 32 × 127 93A60F15VPMF 601 W – 50 m/s from Winterthur (Austria) in a modern CNC gear grinding machine

HOFLER RAPID 1250 (Germany). The initial rotation speed was $S_0 = 0,5\,\text{m/min}$, and the further one was $S_0 = 3\,\text{m/min}$. Wheel fixing was carried out after machining four teeth. The roughness of the finished surface is R_a = 0,63 – 1,25 μm.

5 Conclusions

The theoretical analysis of the conditions for increasing the accuracy and productivity of gear machining in gear grinding operations is carried out. The expediency of gear grinding using the profile copy method is shown. Compared to milling, this method has more technological capabilities. It provides increased accuracy and machining productivity due to the implementation of the dead-stop grinding scheme, which reduces the elastic displacements that occur in the technological system due to uneven removed stock. In this case, the main part of stock removal is carried out in terms of high-performance deep grinding. For the implementation of gear grinding using the profile copy method, an analytical ratio has been obtained to determine the lateral feed elastic displacement that occurs after each pass. Using this ratio allows achieving high machining productivity with the required accuracy. It has also been found out that it is possible to increase machining accuracy and productivity while milling by increasing the refinement of the wheel pass by reducing the conditional cutting stress. This can be achieved by using high porosity grinding wheels, providing a decrease in the friction intensity in the cutting zone due to their high cutting ability.

References

1. Lischenko, N.V., Larshyn, V.P., Nezhebovskiy, V.V.: Studying of the quality of the surface layer of gears with profile grinding. Cutt. Tools Technol. Syst. **89**(101), 88–99 (2018)
2. Riabchenko, S.V.: Grinding gears with disc wheels made of superhard materials. Bull. Kharkiv Petro Vasylenko Natl. Tech. Univ. Agric. **115**, 243–246 (2011)
3. Undewiss, S., Miller, B.: Grinding large module gears. Gear solut. 35–45 (2010)
4. Lishchenko, N.V., Larshin, V.P.: Profile gear grinding temperature determination. In: Proceedings of the 4th International Conference on Industrial Engineering. Lecture Notes in Mechanical Engineering, pp. 1723–1730 (2018)
5. Al Quran, F.M.F.: Theoretical corroboration of the selection criteria of the breaking-in and shape-copy gear teeth grinding methods. Int. J. Mech. Prod. Eng. Res. Dev. **8**(1), 389–392 (2018)
6. Kovalchuk, A.N., Nezhebovskiy, V.V.: Efficiency of using the GLOBAL PERFOMANCE 122210 coordinate measuring machine for measuring gear parts. Bull. Kharkiv Petro Vasylenko Natl. Tech. Univ. Agric. **101**, 214–225 (2010)
7. Kito, Y., Katsuma, T., Yanase, Y., Nose, Y.: Latest technologies for high-precision, high-efficiency gear grinding processing. Mitsub. Heavy Ind. Tech. Rev. **52**(3), 5–8 (2015)
8. Matarneh, M.E.: Improvement of abrasive and edge cutting machining efficiency through theoretical analysis of physical conditions. Int. J. Mech. Prod. Eng. Res. Dev. **8**(2), 249–262 (2018)
9. Stachurski, W., Midera, S., Kruszynski, B.: Determination of mathematical formulae for the cutting force F C during the turning of C45 steel. Mech. Mech. Eng. **16**(2), 73–79 (2012)

10. Patil, R.A., Gombi, S.L.: Experimental study of cutting force on a cutting tool during machining using inverse problem analysis. J. Braz. Soc. Mech. Sci. Eng. **40**, 494 (2018)
11. Atlantic Gear Tooth Profile Grinding. http://www.atlantic-schlifkrugi.ru/fileadmin/redaktion/bilder/downloads/kurzinformatinen/EN_Zahnflankenprofilschleifen_01.pdf. Accessed 15 May 2019
12. Nishimura, Y., Toshifumi, K., Yuji, A., Yoshikoto, Y., Koichi, M.: Gear grinding processing developed for high-precision gear manufacturing. Mitsub. Heavy Ind. Tech. Rev. **45**(3), 33–38 (2008)
13. Zaborowski, T., Ochenduszko, R.: Grinding burns in the technological surface of the gear teeth of the cylindrical gears. Mechanik **10**, 135–139 (2017)
14. Novikov, F.V., Riabenkov, I.A.: Improved gear grinding gears. Bull. Natl. Tech. Univ. «KhPI» Technol. Mech. Eng. **33**(1205), 138–144 (2016)
15. Novikov, F.V.: Mathematical Modeling and Optimization of Metalworking Processes. Simon Kuznets Kharkiv National University of Economics, Kharkiv (2014)
16. Iakimov, O.O.: Influence of intermittent grinding wheel design on geometrical parameters of quality of the processed surface. Cutt. Tool. Technol. Syst. **85**, 323–330 (2015)
17. Tonkonogiy, V.M., Dmitrieva, C.Yu., Yakimov, A.A.: Prevention of the occurrence of parametric instability in the grinding of high-precision gears with intermittent elbor circles. Mod. Technol. Eng. **9**, 206–215 (2014)
18. Lavrinenko, V.I., Novikov, M.V.: Extra materials in mechanical engineering: encyclopaedic handbook. V. Bakul Institute for Superhard Materials of the NAS of Ukraine, Kyiv (2013)
19. Siziy, YuA, Stalinskyi, D.V.: Grinding Dynamics and Thermophysics. Energostal, Kharkiv (2016)