JOURNAL OF ENGINEERING SCIENCES
ЖУРНАЛ ІНЖЕНЕРНИХ НАУК
ЖУРНАЛ ИНЖЕНЕРНЫХ НАУК
Web site: http://jes.sumdu.edu.ua
DOI: 10.21272/jes.2018.5(1).a1 Volume 5, Issue 1 (2018)

UDC 621.923.1

Profile Gear Grinding Temperature Reduction and Equalization

Lishchenko N. V.[1], Larshin V. P.[2]

[1] Odessa National Academy of Food Technologies, 112 Kanatna St., Odessa, 65039, Ukraine;
[2] Odessa National Polytechnic University, 1 Shevchenka Av., Odessa, 65044, Ukraine

Article info:
Paper received: December 29, 2017
The final version of the paper received: February 3, 2018
Paper accepted online: March 5, 2018

***Corresponding Author's Address:**
odeslnv@gmail.com

Abstract. The profile gear grinding modes definition technique is developed to provide the uniform residual temperatures after heating and subsequent cooling which predetermine uniform thermal deformations on periphery of a cogwheel when grinding. The initial basis for this is a possibility to determine the gear grinding temperature both on the heating and cooling stages and, besides, it is may be also a choice of the operation cycle structure with and without the working stroke omission. In the interval of the profile gear grinding modes, two variants of the gear grinding working cycle structure with reciprocating displacement of the grinding wheel are considered using the simulation method with an omission and without one of the working stroke. Certain combinations of mode parameters are found in the range of their possible values at which the combination of heating and cooling leads to the lowest residual surface temperature both during and after working stroke.

Keywords: profile gear grinding, gear grinding temperature, heating stage, cooling stage, cycle structure, working stroke, temperature.

1 Introduction

Typically grinding modes are selected according to reference statistical tables [1]. The choice of them is not substantiated by any criterion, for example, a criterion of the absence of grinding burns, a criterion of the grinding wheel life, a criterion for uniform heating of the machining cogwheel on its periphery, etc.

It is known the method of determining the modes of profile grinding in the three successive stages of this operation according to the system-wide principle of stage theory for any technical process. These stages are rough, semifinish, and finish ones and each of them depends on grinding temperature [2]. A peculiarity of the third grinding stage is the need to equalize the temperature heating along the periphery of a cogwheel. There is a rule that at the finishing stage, the infeed value should be such that it would be possible to grind all the cogwheel teeth without dressing the profile grinding wheel [3]. This is due to the fact that after the dressing, the grinding wheel changes its cutting capacity and the position line of the cutting edge. The infeed value at the finishing stage is reduced as the grinding stock for this stage decreases, and at the last grinding working stroke it is not recommended to apply the infeed values less than 0.010...0.015 mm [2]. However, these data are also not substantiated by any objective criterion and are more likely to be the result of practice.

In the paper [4] the three staged structure of the gear grinding operation is analyzed and consists of rough, semifinish and finish stages. Moreover, modes for each stage are selected based on the parameters of the specific material removal rate in $mm^3/(s \cdot mm)$ and the specific material removal in mm^3/mm. However, these are formal indicators which are not related, for example, to the grinding temperature and the grinding wheel wear.

The purpose of the paper is to improve the method of determining the grinding modes on the last finish (third) stage of the machining cycle by establishing a connection between formal indicators mentioned and the grinding temperature.

2 Research Methodology

2.1 Initial equations

One of the requirements for the finish (third) stage of machining is to ensure a uniform heating of a cogwheel by eliminating the heat accumulation on the periphery of the cogwheel. Thus, the criterion for optimizing the grinding operation at this stage may be the temperature of the grinding as one of the reasons that determine the cogwheel heat content. The temperature field at the heating stage is described by a mathematical dependence, which is a solution of a one-dimensional differential equation of heat conductivity. To determine the temperature $T_H(x,\tau_H)$ at the heating stage, we can use the equation [5]

$$T_H(x,\tau_H) = \frac{2q}{\lambda}\sqrt{a\tau_H}\,\mathrm{ierfc}\frac{x}{2\sqrt{a\tau_H}} + T_0\,, \qquad (1)$$

in which by denoting $\frac{x}{2\sqrt{a\tau_H}} = \xi$, we remind the well-known relations

$$\mathrm{ierfc}\,\xi = \left[\frac{1}{\sqrt{\pi}}\exp(-\xi^2) - \xi\,\mathrm{erfc}\,\xi\right];\ \mathrm{erfc}\,\xi = 1 - \mathrm{erf}\,\xi\,;$$

$$\mathrm{erf}\,\xi = \frac{2}{\sqrt{\pi}}\int_0^{\xi}\exp(-\varepsilon^2)d\varepsilon.$$

In the formula (1) q is the heat flux density (W/m^2), a stands for the temperature conductivity (m^2/s), λ for the heat conductivity (W/(m·K)), x for the dimensional coordinate along the depth of the surface layer (m), $\tau_H = 2h_H / V_f$ for the maximum dimensional heating time at the heating stage (s), V_f for the velocity of the source in the direction of the z axis (axial feed or velocity of the part, m/s), h_H for the maximum value of the provisional value h $\left(0 \le h \le h_H\right)$ at the heating stage, that is, the actual half-width of the real heat source (m), T_0 is the initial temperature of the machining workpiece (room temperature, constant value).

The density of the heat flux q is obtained by averaging the instantaneous value of this parameter $q(r_x)$, and taking into account for each point of the involute profile with an instant radius vector [6]

$$q(r_x) = e_c\psi\frac{dQ}{dS_c} = \frac{P}{V_f\,S_{cc}}\psi\frac{V_f\,t_n(r_x)}{\sqrt{D t_v(r_x)}}\,, \qquad (2)$$

where e_c and Q are the specific grinding energy and material removal rate (in J/mm^3 and mm^3/s), S_c stands for the contact area (m^2), P for the grinding power (W), S_{cc} for the cross-section area in the grinding wheel movement direction (m^2), ψ for the share of heat into the workpiece, $t_n(r_x)$ and $t_v(r_x)$ are the normal and vertical depths of cutting at an involute profile separate point (m), D is the instant diameter of the grinding wheel in the considered cross-section of its profile (m).

To determine the temperature at the cooling stage, which follows immediately after heating, with the initial conditions obtained during the heating stage, the following equation can be used [5]:

$$T_C(x,t_C) = \int_0^{\infty}\Bigg[\frac{1}{2\sqrt{\pi a t_C}}\left\{\exp\left(-\frac{(x-x')^2}{4at_C}\right) + \exp\left(-\frac{(x+x')^2}{4at_C}\right)\right\} -$$
$$-A\exp\left(at_C A^2 + A\left(x+x'\right)\right)\times\mathrm{erfc}\left(\frac{x+x'}{2\sqrt{at_C}} + A\sqrt{a\cdot t_C}\right)\Bigg] f\left(x'\right)dx' +$$
$$+aA\int_0^{t_C}\Bigg[\frac{\exp\left(-\frac{x^2}{4a\left(t_C-\tau_C\right)}\right)}{\sqrt{\pi a\left(t_C-\tau_C\right)}} - A\exp\left(aA^2\left(t_C-\tau_C\right) + Ax\right)\times$$
$$\times\mathrm{erfc}\left(\frac{x}{2\sqrt{a\left(t_C-\tau_C\right)}} + A\sqrt{a\left(t_C-\tau_C\right)}\right)\Bigg]\varphi\left(\tau_C\right)d\tau_C\,, \qquad (3)$$

in which

$$f(x') = \frac{2q\sqrt{a\tau_H}}{\lambda}\left[\frac{1}{\sqrt{\pi}}\exp\left(-\frac{x'^2}{4a\tau_H}\right) - \frac{x'}{2\sqrt{a\tau_H}}\mathrm{erfc}\left(\frac{x'}{2\sqrt{a\tau_H}}\right)\right] + T_0,$$

where $\tau_H = 2h_H / V_f$ stands for the maximum heating time at the heating stage (s), t_C for cooling time (s); $A = \frac{\alpha_h}{\lambda}$ for the reduced heat transfer coefficient, α_h for heat transfer coefficient (W/(m^2·K)), $\varphi\left(\tau_C\right)$ for the starting temperature of the lubricoolant (°C), which can vary over the cooling time interval τ_C, and $0 \le \tau_C \le t_C$.

2.2 Technique for decision making

Thus, with a known type and a method of supplying the lubricoolant, for controlling the temperature at the cooling time interval it is possible to control the α_h coefficient value (convection coefficient), the magnitude of the output temperature of the lubricoolant $\varphi(\tau_C)$, and the grinding modes, that is, to regulate the vertical cutting depth t_v and the axial feed V_f. Moreover, the value of t_v affects the maximum heating temperature as well as the value of V_f determines the time of heating and cooling, which affects both on the T_H and the achieved temperature level $T_C(x,t)$ at the end of the cooling stage in the "heating-coolin" cycle on each working stroke. Thus, under otherwise identical conditions (cutting speed, grinding wheel characteristics, lubricoolant kind, etc.), the control and optimization parameters may include elements of cutting modes: t_v and V_f.

The cooling time $0 \le t_C \le \infty$ is counted from the heating interval end. The task is to determine such mode parameters t_v and V_f, under which the heating stage with the surface temperature $T_{\max} = T(0,\tau_H)$ (Figure 1, line 1) will be changed by a cooling stage at which the temperature will change in the required manner (Figure 1, line 2). The control is to choose the grinding modes t_v and V_f which will result in the absence of heat accumulation (Figure 1, line 2): T_{C1}, T_{C2}, T_{C3} and T'_{C1}, T'_{C2}, and T'_{C3} are necessary (completely cooled surface) and actual (not completely cooled surface) surface temperature dependence on time in the first, second and third working passes, respectively.

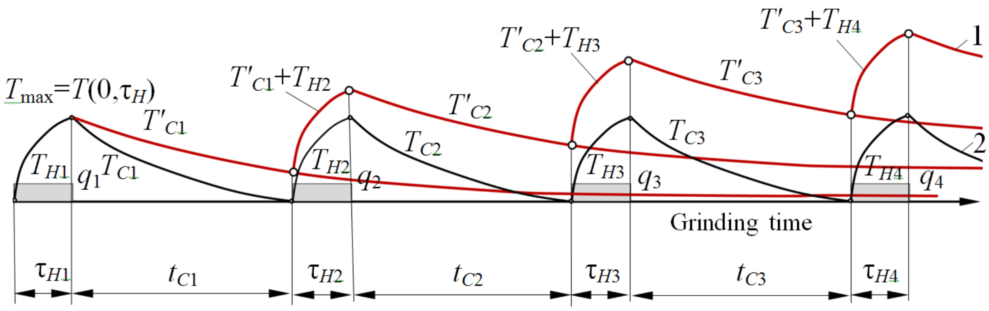


Figure 1– Grinding temperature changing with accumulation heat energy (line 1) and without it (line 2)

With a local increase in the temperature of individual grinded sections of the toothed surface, the temperature field is asymmetric in the symmetric body of the workpiece. This will lead to temperature ununiformed deformations of the heated sections, and, in consequence, to the cogwheel accuracy parameters deviations after the cogwheel cooling.

3 Results

3.1 Gear grinding with and without working stroke omission

There are two structures of the "heating-cooling" cycle: the up–and-down grinding without working stroke omission (Figure 2 a) and the only up grinding with the omission (Figure 2 b). In the cycle structure without working stroke omission the grinding wheel makes a working stroke with the length of $l_1 + B + l_2$ (B is the width of the tooth rim, l_1 and l_2 are the grinding wheel approach and overtravel lengths), i.e. consistently passes the points 1-2-3 (up grinding), which are located in the beginning, middle and end of the length of the tooth rim (Figure 2 a). On the reverse working stroke, the grinding wheel makes reverse displacement (down grinding), i.e. consistently passes the points 3-2-1. In this case, the greatest amount of heating gets the point 3, because at this point, the cooling time is the smallest and is equal to

$$t_1 = \frac{2l_2}{V_f} \qquad .(4)$$

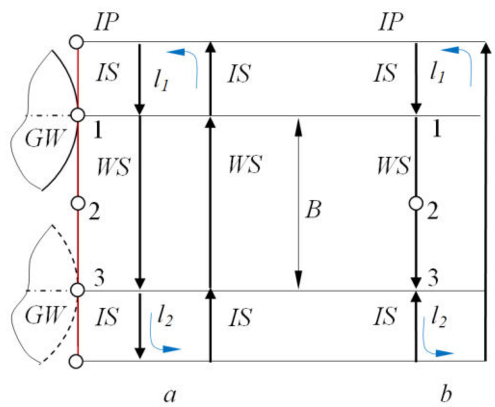


Figure 2 – The grinding cycle structures, in which *GW* is a grinding wheel; IP, IS and WS are the initial position, single and working strokes respectively

When repeating the "heating-cooling" cycle, the point 1 gets the greatest heating amount, because at this point, the cooling time is the smallest and is equal to

$$t_2 = \frac{2l_1}{V_f}. \quad (5)$$

In the structure of the cycle with the working stroke omission, the grinding wheel makes a working stroke $l_1 + B + l_2$ consistently passing the points 1-2-3 (up grinding), which belong to the beginning, middle and end of the tooth rim length (Figure 2 b). Before the reverse stroke the grinding wheel does not move radially to the cutting depth t_v that is this reverse stroke is idle and the grinding wheel makes idle stroke with the length of $l_2 + B + l_1$ (points 3-2-1 without heating) getting to the initial position. When repeating the "heating-cooling" cycle, heating at the up grinding receives the point 1, that is at this point, the cooling time is the smallest and is equal to

$$t_3 = \frac{2l_1 + 2l_2 + 2B}{V_f}. \quad (6)$$

3.2 Reduction and equalization of temperature

Assuming $l_1 = l_2 = l$ for the structure with the working stroke omission we can see that cooling time according to formula (6) increases more than twice because the ratio of t_3 / t_1 is equal to the t_3 / t_2 and is $2(2l + B)/2l = 2 + B/l$.

Next, we introduce the following symbols for the surface temperature (i.e. x = 0) for heating and cooling: $T_H(0,\tau_H) = T_H$ and $T_C(0,t_C) = T_C$, respectively. For both structures of the cycle the influence of the axial feed V_f and the vertical depth of cutting t_v on the heating time τ_H and the heating temperature T_H by the formula (1) and the cooling temperature T_C by the formula (3) are established with the following initial data: x = 0 (on surface); e_c = 50 J/mm^3; ψ = 0,8; profile angle α = 20° or $\frac{\alpha\pi}{180^o}$ rad; D = 400 mm; a = 5.68·10^{-6} m^2/s; λ = 24 W/(m·K); α_h = 10 000 W/(m^2·K); $A = \frac{\alpha_h}{\lambda}$ = = 416,67 m^{-1}; T_0 = 0 °C; $\varphi(\tau_C)$ = 15 °C; $l_1 = l_2$ = 7.86 mm; B =24 mm. The axial feed V_f varies in the range of 500...7000 mm/min, and the vertical depth of grinding t_v takes the following fixed values: t_v = 0.015 mm (Tables 1, 3) and t_v = 0.074 mm (Tables 2, 4). With increasing V_f for t_v = const (Tables 1, 2), the heating time τ_H decreases and the heating temperature T_H increases. With the increasing t_v at the same values for V_f (pairs of Tables 1, 2, as well as Tables 3, 4), the heating time τ_H and heating temperature T_H increase.

For the cycle with the working stroke omission (Tables 3, 4), the heating time τ_H and the heating temperature T_H did not change compared with the previous structure (without working stroke omission), therefore, τ_H and T_H in Table. 3 and Table 4 are not given. There are both cooling time t_C and cooling temperature T_C changing at t_v = 0.015 mm (Table 3) and t_v = 0.074 mm (Table 4). The reason for the difference between the parameters t_C and T_C in cycles with and without working stroke omission is the only one - the increase in cooling time t_C in the cycle structure with working stroke omission.

Table 1 – Influence the V_f on the τ_H, T_H, t_C, and T_C for the cycle structure without working stroke omission at t_v = 0.015 mm

V_f, mm/min	500	1000	1500	2000	2500	3000	3500
τ_H, s	0.2939	0.1469	0.09798	0.07348	0.05879	0.04899	0.04199
T_H, °C	42.42	59.99	73.47	84.84	94.86	103.91	112.24
t_C, s	1.8868	0.9434	0.6289	0.4717	0.3774	0.3145	0.2695
T_C, °C	11.598	12.002	12.789	13.903	14.906	15.606	16.556
V_f, mm/min	4000	4500	5000	5500	6000	6500	7000
τ_H, s	0.03674	0.03266	0.02939	0.02672	0.02449	0.02261	0.021
T_H, °C	119.986	127.268	134.143	140.696	146.956	152.957	158.731
t_C, s	0.23585	0.20964	0.18868	0.17153	0.15723	0.14514	0.13477
T_C, °C	17.494	18.416	19.317	20.205	21.072	21.922	22.755

Table 2 – Influence of V_f on τ_H, T_H, t_C, T_C for cycle structure without working stroke omission at t_v = 0.074 mm

V_f, mm/min	**500**	**1000**	**1500**	**2000**	**2500**	**3000**	**3500**
τ_H, c	0.65287	0.32644	0.21762	0.16322	0.13057	0.10881	0.09327
T_H, °C	140.428	198.595	243.228	280.856	314.006	343.977	371.537
t_C, c	1.88678	0.94339	0.62893	0.4717	0.37736	0.31446	0.26954
T_C ,°C	18.61	26.35	33.541	40.264	46.604	52.618	58.348
V_f, mm/min	**4000**	**4500**	**5000**	**5500**	**6000**	**6500**	**7000**
τ_H, c	0.08161	0.07254	0.06529	0.05935	0.05441	0.05022	0.04663
T_H, °C	397.19	421.284	444.072	465.747	486.456	506.32	525.433
t_C, c	0.23585	0.20964	0.18868	0.17153	0.15723	0.14514	0.13477
T_C ,°C	63.832	69.097	74.168	79.065	83.805	88.402	92.869

Table 3 – Influence the V_f on the t_C and T_C for the cycle structure with working stroke omission at t_v = 0.015 mm

V_f, mm/min	500	1000	1500	2000	2500	3000	3500
t_C, c	9.53357	4.76678	3.17786	2.38339	1.90671	1.58893	1.36194
T_C, °C	12.604	11.976	11.657	11.494	11.426	11.42	11.458
V_f, mm/min	4000	4500	5000	5500	6000	6500	7000
t_C, c	1.1917	1.05929	0.95336	0.86669	0.79446	0.73335	0.68097
T_C, °C	11.529	11.624	11.738	11.867	12.008	12.158	12.317

Table 4 – The same as Table 3 at t_v = 0.074 mm

V_f, mm/min	500	1000	1500	2000	2500	3000	3500
t_C, c	9.53357	4.76678	3.17786	2.38339	1.90671	1.58893	1.36194
T_C, °C	13.57	14.342	15.457	16.726	18.078	19.477	20.902
V_f, mm/min	4000	4500	5000	5500	6000	6500	7000
t_C, c	1.1917	1.05929	0.95336	0.86669	0.79446	0.73335	0.68097
T_C, °C	22.339	23.78	25.218	26.651	28.074	29.487	30.889

Let's perform a comparison of the cooling temperatures for two grinding cycle structures at t_v = 0.015 mm (Fig. 3, *a*) and t_v = 0,074 mm (Fig. 3, *b*). There are three ways to achieve the lowest cooling temperature T_C = 11.6°C for t_v = 0,015 mm (Fig. 3, *a*): 1) when grinding without working stroke omission with axial feed V_f = 0.5 m/min (point *A*), 2) when grinding with working stroke omission with axial feed V_f =1.8308 m/min (point *B*, and 3) the latter at V_f = 4226.9 mm/min (point *C*).

There are two ways to achieve the lowest cooling temperature T_C = 18.6 °C for t_v = 0.074 mm (Figure 3 b) when grinding without working stroke omission with axial feed V_f = 0.5 m/min (point *D*; 2) when grinding with working stroke omission with an axial feed V_f = 2.6444 m/min (point *E*).

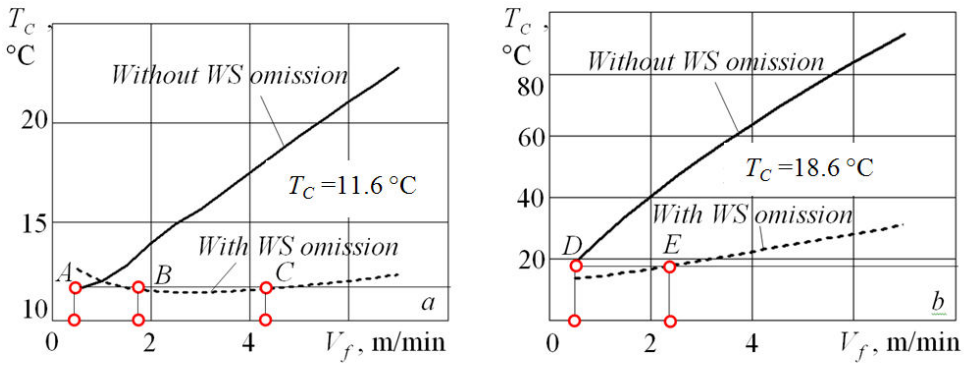
The time to machine by gear grinding both without and with working stroke omission can be determined by the following formulas, respectively

$$T_M = \left(\frac{B + l_1 + l_2}{V_f} \frac{z_{\max}}{t_v} + \frac{T_{IND}}{60} \right) z \,; \tag{7}$$

$$T_O = \left(\frac{B + l_1 + l_2}{V_f} 2 \frac{z_{\max}}{t_v} + \frac{T_{IND}}{60} \right) z \,, \tag{8}$$

where B stands for the width of the tooth rim (B =24 mm), z for the number of cogwheel teeth (z = 40), $l_1 = l_2$ = 7.86 mm, $z_{\max}$ for the grinding stock for machining a cogwheel in the finish (third) stage ($z_{\max}$ = 0,1 mm), T_{IND} for the indexing time (cogwheel angular turning for one tooth, T_{IND} = 4 s).

To ensure the lowest cooling temperature T_C = 11.6 °C, the minimum time to machine is equal to 7.632 min (Table 5) which is obtained in the with working stroke omission cycle structure at t_v = 0.015 mm and V_f = 4226.9 mm / min.



a b

Figure 3 – Cooling temperature T_C vs axial feed V_f for different grinding cycle structures at t_v = 0.015 mm (a) and t_v = 0.074 mm (b)

Table 5 – Determining the time to machine in gear grinding

Grinding cycle structure of the	Without working stroke omission	With working stroke omission	
The lowest cooling temperature T_C = 11.6 ° C at t_v = 0.015 mm			
Grinding conditions	V_f =500 mm/min (point *A*)	V_f =1830.8 mm/min (point *B*)	V_f = 4226.9 mm/min (point *C*)
Time to machine, min	23.852	14.238	7.632
The lowest cooling temperature T_C = 18.6 °C at t_v = 0.074 mm			
Grinding conditions	V_f =500 mm/min (point *D*)	V_f = 2644.9 mm/min (point *E*)	
Time to machine, min	6.961	4.29	

To provide the cooling temperature T_C = 18.6 °C (more than 11.6 °C), the minimum time to machine T_M = 4.29 min (Table 5) is obtained in the cycle structure with working stroke omission at t_v = 0.074 mm and V_f = 2644.9 mm/min. From these five variants (points *A*, *B*, *C*, *D*, and *E* in Figure 3) we choose the variant with the minimum value T_C = 11.6 °C (points *A*, *B*, *C*), since the theoretical value is T_C = 0. It can be seen (Table 5) that the minimum time to machine T_M = 7.632 min is obtained in the cycle structure with working stroke omission at t_v = 0.015 mm and V_f = 4226.9 mm/min (T_C = 11.6 °C).

Thus, the study of the gear grinding temperature models (1) and (3) both at the heating (1) and cooling (3) stages allowed to recommend the working stroke omission in the structure of this operation and to assign the appropriate gear grinding modes for the finish (third) gear grinding stage both for t_v = 0.015 mm (points *A*, *B*, *C* in Figure 3) and t_v = 0.074 mm (points *D*, *E*).

4 Conclusions

As the depth of gear grinding t_v increases the maximum cooling temperature T_C increases as well. In the gear grinding cycle structure with working stroke omission cooling time t_C is greater than that without working stroke omission. As the axial feed V_f increases the cooling temperature T_C for the cycle structure with working stroke omission at t_v = 0.015 mm and t_v = 0.074 mm does not practically change, while for the cycle structure without working stroke omission the cooling temperature T_C increases. The smallest cooling temperature T_C is reached at t_v = 0,015 mm, so it is expedient to accept the minimum possible vertical depth of grinding t_v on the finishing (third) gear grinding stage, for example, for the finishing stage we take t_v = 0,015 mm.

Moreover, in this stage, the axial feed V_f is chosen not only from the condition of maximum productivity (maximum V_f), but also from the condition of surface roughness (in the interval of V_f from 1830.8 to 4226.9 mm/min) and the smallest elastic deformation in the gear grinding system.

References

1. Kalashnikov, S. N. et al. (1990). *Proizvodstvo zubchatykh koles: Handbook*. Moscow, Mashinostroyeniye [in Russian].
2. Lishchenko, N. V. (2016). Opredeleniye intensivnosti zuboshlifovaniya na osnove analiticheskogo uravneniya evol'venty. *Suchasni tekhnologii v mashinobuduvanni*, Issue 11 [in Russian].
3. Dekapolitov, M. I. (2011). *Povysheniye effektivnosti profil'nogo zuboshlifovaniya tsilindricheskikh koles putem rascheta parametrov staticheskoy naladki: Ph.D. thesis*. Specialties 05.02.07 – Tekhnologiya i oborudovanie mekhanich. i fiziko-tekhnologicheskoy obrabotki; 05.02.08 – Tekhnologiya mashinostroyeniya. Moscow.
4. Nishimura, Yu., Katsuma, T., Ashizawa, Y., Yanase, Y., Masuo, K. (2008). Gear grinding processing developed for high-precision gear manufacturing. *Mitsubishi Heavy Industries, Ltd. Technical Review*, Vol. 45, No. 3, 33–38.
5. Carslaw, H. S., Jaeger, J. C.(1959). *Conduction of heat in solids (2nd ed.)*. London, Oxford University Press.
6. Larshin, V. P. (1999). Tekhnologiya mnogonitochnogo rez'boshlifovaniya pretsizionnykh khodovykh vintov. *Proceedings of Odessa National Polytechnic University*, Odessa, Issue 2(8), 87–91 [in Russian].

Зниження та вирівнювання температури профільного зубошліфування

Ліщенко Н. В.[1], Ларшин В. П.[2]

[1] Одеська національна академія харчових технологій, вул. Канатна, 112, м. Одеса, 65039, Україна;
[2] Одеський національний політехнічний університет, просп. Шевченка, 1, м. Одеса, 65044, Україна

Анотація. Розроблено методику визначення режимів зубошліфування на третьому завершальному етапі профільного зубошліфування на верстаті з ЧПК, виходячи із забезпечення вирівнювання температури по периферії і найменшого нагрівання зубчастого колеса. Для цього використано формули для визначення температури зубошліфування на етапі нагрівання та охолодження оброблюваної поверхні. На етапі нагріву температурне поле поширюється по глибині поверхневого шару і змінюється в часі. У момент закінчення етапу нагріву, миттєве температурне поле, яке загасає по глибині поверхневого шару, є початковою умовою для визначення температури на етапі охолодження. Тому температура охолоджувальної поверхні залежить не тільки від регульованого часу охолодження, але також від миттєвого розподілу температури в поверхневому шарі, яке враховується як початкова умова при моделюванні на етапі охолодження. Знайдено оптимальні умови охолодження, в тому числі за рахунок пропусків робочих ходів, які реалізовані зубошліфуванням без установки глибини різання.

Ключові слова: профільне зубошліфування, температура зубошліфування, етап нагріву, етап охолодження, структура циклу, пропуск робочого ходу, вирівнювання температури.