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This article is dedicated to the 95th birthday of Professor A.V. Yakimov (born March 16, 1925)

INTERMITTENT GRINDING TEMPERATURE MODELING FOR GRINDING SYSTEM STATE MONITORING

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ABSTRACT

A dry and wet intermittent grinding temperature mathematical model for the thermal macro- or micro-cycle was developed and studied. The heating stage corresponds to the wheel cutting segment passage time through the every contact zone point. The cooling stage corresponds to the passage time of the grinding wheel groove (or pore) through the point mentioned. The dry intermittent grinding temperature field is formed by temperature field superposition during the indicated both heating and cooling cycle stages under the action of heat flux on each point of the surface being ground. While during wet intermittent grinding with grinding fluid through the grooves (or pores) of the intermittent grinding wheel, the temperature field formed at the heating stage is the initial condition for determining the temperature field at the forced cooling stage. Based on the obtained model of the intermittent grinding temperature field the geometrical parameters of the discontinuous (slotted, segmented, high porous) grinding wheel are found and determined for the grinding with intermittent grinding wheel as follows: the number of cutting sections on the wheel and the duty factor of the period of heat flux pulses. The wet intermittent grinding temperature field is also formed by summing (stitching) the temperature fields. However, the heat exchange of the surface being ground with the cooling medium, which periodically acts on this surface during the cooling stage, is taken into account in each macro- or micro-cycle of heat flux in intermittent grinding. The presented article is the result of current work carried out as part of the scientific school of Professor A.V. Yakimov who was the founder of intermittent grinding technology and automation of grinding operations.

Keywords: Dry and Wet Grinding; Slotted and Segmented Wheels; High Porous Wheels; Cutting Segment; Non-Cutting Area

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1. INTRODUCTION

The temperature in the grinding zone is one of the factors limiting the performance of grinding operation. To optimize grinding parameters, it is necessary to have true in-formation about the grinding temperature which can be obtained by theoretical methods, theoretical methods with experimental verification, theoretical methods with temperature field simulation, simulation with experimental testing, the only simulation both at the production stage and its preparation. One of the most effective methods of reducing the grinding temperature and, consequently, increasing the productivity of the grinding operation is the use of grinding wheels with a discontinuous working surface. Alternating cutting segments and no cutting grooves (cavities, flutes, pores) on the working surface of such wheels help to improve cutting conditions and effectively remove chips from the cutting zone.

In addition, these grooves on the wheel cutting surface contribute to the effective penetration of the grinding fluid into the cutting zone with all the resulting positive consequences which the grinding fluid provides, to wit: cooling, reducing friction, removing chips, etc.

For more than a century of manufacturing engineering development a huge range of metal cutting and abrasive tools has been created. The working surface of any multipoint cutting tool is a combination of cutting (cutting edges) and non-cutting (chip grooves) elements. In this sense, any cutting process with these tools is intermittent and cyclical, i.e. repetitive with a certain frequency of the tool cutting elements impact on the surface to be machined. It means the heat flux of intermittent process will be impulsive. For example, straight fluted drill has flutes running parallel to the drill axis. The twist drill also is intermittent one, that is, each point of the cylindrical surface formed during drilling will experience an alternate effect of the heating and cooling stages. Other examples of intermittent cutting are the core drill, end mill, segmented (slotted, high porous) grinding wheel, etc. For this reason, the study of the features of cutting with tools that have an intermittent working surface, for example, the study of intermittent grinding when machining parts from hard-to-machine materials, is one of the urgent issues of manufacturing engineering.

With intermittent grinding, a decrease in temperature occurs for two reasons: due to interruption of the heating process (at the stage of heating the surface, the temperature rise stops and is replaced by its drop). This drop is caused not by convective heat transfer (during forced cooling), but by heat removal due to the phenomenon of heat conduction. Heat is removed in the direction from the surface to the depth of the workpiece material. Therefore, it can be argued that this is not forced cooling of the treated surface being ground, but the lack of heating. The first part of this article is devoted to this. Teaching of A. V. Yakimov on intermittent grinding, published in a large number of works, mainly covers this case of temperature reduction. However, the possibility of an additional decrease in temperature during intermittent grinding due to forced cooling of the contact zone while passing over the grinding wheel uncutting segment (the gap) that follows the cutting segment of this wheel has not yet been investigated. The issue of forced cooling model construction for intermittent grinding is discussed in the second part of this article.

2. LITERATURE REVIEW

Intermittent grinding is considered in [1,2], [3,4], [4,6], [7,8], [9,10]. Part of these works contains analytical studies to determine the grinding temperature without taking into account [2], [4, 5], [6,7], [8] and taking into account [7] ,[1], [9], [1] the cooling effect of grinding fluid. For example, an experimental study on the cutting force and the grinding temperature for ceramic face grinding using slotted diamond wheels is presented in [1]. The experimental results show that the temperature of discontinuous grinding is about 40±80 % less than that of continuous grinding, which can reduce the wear and the oxidization of the grinding wheel. A temperature field model for discontinuous face grinding has been established, which can serve as a reference for the optimal design of slotted grinding wheels. An analytical model was established to calculate the curve of temperature distributions in surface grinding with intermittent wheels [2]. In order to predict the numbers of the pulses imposed on the fluctuating temperature profile, a new quantity, the dynamic number of wheel segments in the grinding zone, was defined. The values of peak and valley temperatures are studied. The contributions of segment and groove engaging states to the temperature profiles are of a big difference, reflecting the different effects of segment and groove. After considering the wheel-engaging states, a good matching was obtained between the calculated temperature curve and the measured curve.

Theoretical calculation results show that the intermittent grinding temperature rise is periodic which will reduce the heat accumulation in grinding zone and reduce grinding thermal damage [5]. It was showed that the machining of the teeth of the broaches with a grinding wheel with a discontinuous profile, in comparison with the machining of broaches according to the traditional technology, provides a higher quality of blade surfaces, while the process productivity, compared with the factory technology, increased by 20...26 % [6].

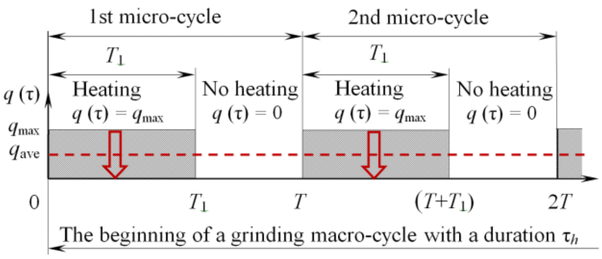


Fig. 1. **Pulsating heat flux q (τ): 0T_1 and T_1T are time intervals of “heating” and “no heating”**

***Source*: compiled by the author**

In work [7], a pulsating heat flux q (τ) scheme was proposed (Fig. 1), containing alternating sections of two types: “heating” and “no heating”. The latter means the heat flux is absent, i.e. q (τ) =0, but it does not mean “cooling”. When the “cooling” is absent, this made it possible to apply the thermal field’s superposition method for the simultaneous action of two (positive and negative) unmoving heat sources, the onset of which is time-shifted by the length T_1 of the heat pulse. Thus, the appearance of each new heat flux pulse is due to a pair of complementary heat sources having the opposite sign and shifted by a value T_1 relative to each other.

A distinctive advantage of intermittent grinding wheels is manifested not only in the possibility of removing chips from the cutting zone, but also in increasing the efficiency of forced cooling the cutting zone through the grinding wheel slots or grooves [8-9]. The performance of the slotted grinding wheel in comparison to other grinding wheels, applying the same coolant nozzle for each, revealed significant improvements in the cooling efficiency [10].

Design of slotted grinding wheels for creep feed grinding processes and the more modern process of high efficiency deep grinding is also relevant [11]. However, there is no information in the literature about the use of high porous grinding wheels as appropriate micro-interrupted ones. In the available literature on the use of high porous grinding wheels, the concept of pulsed (intermittent) thermal action in determining the grinding temperature has not yet been considered [12-14].

In the conclusion of the literature review, it should be noted that the universal approach to determining the intermittent grinding temperature discussed below was previously prepared by the relevant publications [15-17].

3. RESEARCH METHODOLOGY

The review of the technical literature allows us to perform the following classification of discontinuous grinding wheels based on the frequency of the thermal pulses impact on the surface being ground when grinding with interrupted wheels (see Fig. 2).

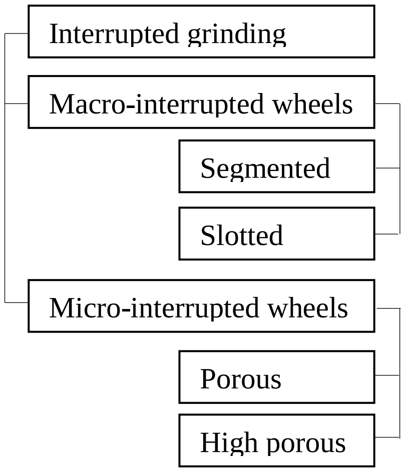


Fig. 2. **Interrupted grinding wheels classification based on the wheels geometrical parameters**
***Source*: compiled by the author**

The slotted grinding wheels are usually constructed from conventional continuous grinding wheels (Fig. 3a and Fig. 3b) by cutting off grooves or slots as it is shown in (Fig. 3c). As a rule, the cutting segments are symmetrically located on the periphery of the grinding wheel. However, the number of cutting segments on such an intermittent wheel is limited, and as a rule, does not exceed 40 pieces. As for highly porous grinding wheels, the number of naturally arranged “segments” (sections of the cutting surface between the pores of the wheel) can be an order of magnitude greater.

Therefore, another example of micro-interrupted grinding wheel is the porous or high porous wheels in which the cutting grain areas (cutting section of length l_1) alternate with pore voids (non-cutting section of length l_2).

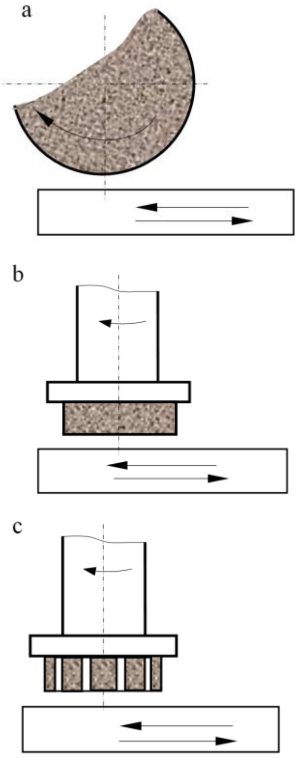
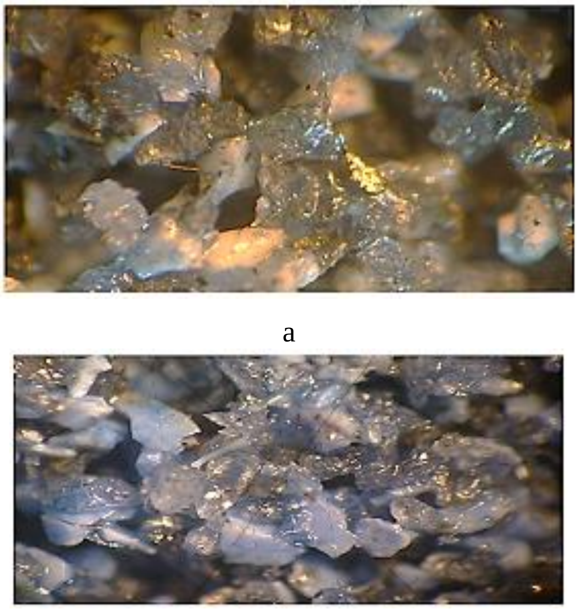


Fig. 3. **Common schemes of continuous (a, b) and intermittent (c) grinding**
***Source*: compiled by the author**

Parameters l_1 and l_2 were measured using a universal measuring microscope UMM-21 when examining the surface of high porous grinding wheels (Fig. 4).



a

b

Fig. 4. **A fragment of the real surface of a highly porous grinding wheel obtained for the wheel specifications WG946Hs12Vs (a) and 3SG46Hs12Vs (b)**
***Source*: compiled by the author**

The result of microscopic examination of the actual surface of highly porous grinding wheels can be represented as an idealized scheme (Fig. 5) which shows the variable parameters l_1 and l_2 for subsequent investigation.

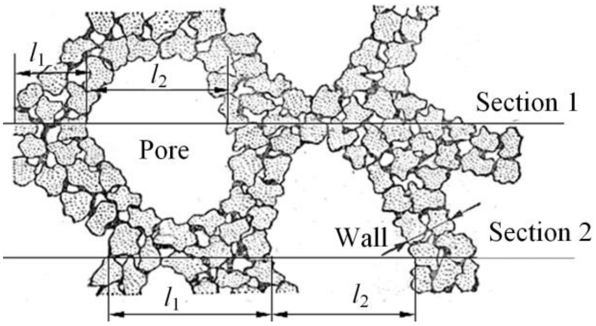


Fig. 5. **A fragment of the high porous grinding wheel made for the subsequent investigation**
***Source*: compiled by the author**

Thus, the grinding wheel surface geometrical parameters l_1 (cutting segment) and l_2 (not cutting cavity or flute) are irregular ones. However, due to the known inertia of the thermal field, it is likely that the corresponding equivalent of the regular calculation parameters can be found for these irregular parameters. To understand this idea, it is necessary to imagine a certain sequence of repeating events of the "pulse-pause" type with a variable repetition period (Fig. 1), then

$$T = \frac{l_1}{V_{gw}} + \frac{l_2}{V_{gw}}, \quad (1)$$

where V_{gw} is the grinding wheel linear speed (cutting speed) in m/s.

The terms on the right-hand side of formula (1) for a highly porous grinding wheel are variables (see Fig. 5). Consequently, the period T of repeating events "pulse-pause" will also be variable. Now we can theoretically prove that there is such a repetition frequency of the regular "pulse-pause" signal, i.e. at T = const, when the average surface temperature in both cases will be the same. Thus, the random nature of the changes in parameters l_1 and l_2 can be adequately taken into account by a certain calculated periodic signal of a pulsed heat flux, for which l_1 = const and l_2 = const. This assumption allows us to solve the problem of determining the temperature of macro- and micro-intermittent grinding from a single point of view.

The case just considered of converting random irregularity to deterministic regularity is not the most difficult task. More difficult is the task of accounting for cooling during intermittent grinding, according to which, in the area of action of the cutting segment (ledge) l_1, heat flow enters the material, while in the area where the cutting segment is absent the heat flow is not simply absent. It becomes negative, i.e. directed not inward, but outward from the heated surface into the grinding fluid (Fig. 6).

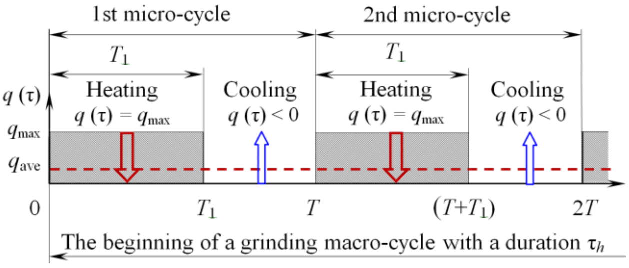


Fig. 6. **Pulsating heat flux $q(\tau)$ containing a periodic sequence of micro-cycles "heating-cooling" with a period T: $0T_1$ and T_1T are heating and cooling time intervals**
***Source*: compiled by the author**

4. DRY AND WET INTERMITTENT GRINDING MODELS

Thus, the thermal scheme of intermittent grinding can be represented by a sequence of heat flux pulses $q(\tau)$, which is characterized by a period T, a period duty factor $s = T_1/T$, and the maximum q_{max} and average q_{ave} values of the heat flux as it is shown in Fig. 1 and Fig.6. In accordance with the two accepted design schemes (Fig. 1 and Fig. 6), the theoretical prerequisites for determining the temperature field during intermittent grinding are sequentially considered below.

4.1. Dry intermittent grinding model

During the operation of the cutting segment (heating), a heat flux $q(\tau) = q_{MAX}$ acts in the contact zone, and during the absence of cutting (no heating or cooling) $q(\tau) = 0$ (Fig. 1). Thus, the heat flux acting on the surface being grinding can be represented as the following step function [18]

$$q(\tau) = \begin{cases} 0, & \tau < 0 \\ q_{max}, nT < \tau < (nT + T_1), & n = 0,1,\ldots . \\ 0, \quad nT + T_1 < \tau < (n+1)T, & n = 0,1,\ldots \end{cases} \quad (2)$$

A continuous sequence of macro- or micro-cycles is located on heating stage time interval the duration of which for both continuous and intermittent wheels is determined by the heat source action time τ_h, which can be determined by the formula

$$\tau_h = \frac{2h}{V} = \frac{\sqrt{D\,t_{GR}}}{V}, \qquad (3)$$

where: $2h$ is the contact zone length, m; V is the workpiece velocity in the feed direction, m/s; D is the grinding wheel diameter, m; t_{GR} is the depth of cut in grinding, m.

As the number of cutting segments on the periphery of a wheel increases, the number of periodic cycles increases too, while the period T of each cycle decreases (Fig.1 and Fig. 6). Therefore, it is necessary to obtain the dependence of the intermittent grinding temperature only on the geometric parameters of intermittent grinding wheels, which include the number of cutting segments on the wheel and the duty factor of the circumferential step.

In addition, the works mentioned in the review does not take into account an important additional condition that must be met with respect to all discontinuous grinding wheels which compared with the grinding temperature, namely: there must be the same removal metal rate.

The temperature is calculated using the following equation [18]

$$\Theta_{SUM} = \Theta_R\left(q_{\text{ave}}\right) + \Theta_P\left(q_{\max}\right). \qquad (4)$$

The first component in equation (4) continuously increases and depends on the average level of heat flux q_{ave} and

$$\Theta_R = \frac{2\,q_{\text{ave}}}{\lambda}\sqrt{\frac{a\,\tau}{\pi}} = \frac{2\,q_{\max}}{\lambda}\frac{T_1}{T}\sqrt{\frac{a\,\tau}{\pi}}, \qquad (5)$$

where: τ is the heat source action time in the interval of $0 \le \tau \le \tau_h$; $q_{\text{ave}} = q_{\max}\dfrac{T_1}{T}$ and $q_{\max}$ are the average and maximum heat flux during the macro- or micro-cycle period respectively, W/m^2; λ is the material thermal conductivity, W/(m·°C); a is the thermal diffusivity, m^2/s.

The second component in equation (3) is the pulse periodic one which depends on both the maximum level of the heat flux $q_{\max}$ and its length over time in the cycle period (Fig. 1 and Fig. 6).

In formulas (6) and (7) the following designations are used: $s = \dfrac{T_1}{T}$ is the duty factor for periodic heat flux (Fig. 1), i.e. the fraction of one heat flux period in which an intermittent grinding wheel is active; $p = \dfrac{\tau}{T}$ is the dimensionless (relative) time in the interval of the grinding macro- or micro-cycle $0 \le \tau \le T$.

The mathematical model (4)-(8) for determining the temperature from a pulsating heat flux allows you to determine this temperature at any time in the time interval of steady-state temperature values [17]. The disadvantage of this model is the uncertainty of this time interval, which occurs after the end of the temperature transition process. This constrains the use of the model (4)-(8) for designing intermittent grinding wheel optimal constructions and corresponding formulations of high porous grinding wheels.

In the interval of $0 < p < s$ (heating)

$$\Theta_p = \frac{2\,q_{\max}}{\lambda}\sqrt{\frac{aT}{\pi}}\left[(1-s)\sqrt{p} - \frac{1}{\sqrt{\pi}}\,I(s,p)\right]. \qquad (6)$$

In the interval of $s < p < 1$ (no heating)

$$\Theta_p = \frac{2\,q_{\max}}{\lambda}\sqrt{\frac{aT}{\pi}}\left[(1-s)\sqrt{p} - \sqrt{(p-s)} - \frac{1}{\sqrt{\pi}}\,I(s,p)\right]. \qquad (7)$$

Here

$$I(s,p) = \int_0^{\infty} \frac{\left[(1-s)\exp\left(-\xi^2\right) - \exp\left\{-(1-s)\,\xi^2\right\} + s\right]\exp\left(-p\xi^2\right)}{\xi^2\left[1-\exp\left(-\xi^2\right)\right]}\,d\xi\,\cdot. \qquad (8)$$

That is why, a new mathematical formula for determining the intermittent grinding temperature is proposed instead of and based on formulas (4)-(8), to wit:

$$\Theta_{SUM} = \frac{q_{\text{ave}}}{\lambda}\sqrt{\frac{a}{\pi}}\left(2\sqrt{\tau_h} + f(s)\sqrt{T}\right), \qquad (9)$$

where: $f(s) = A\sqrt{s} + \frac{B}{\sqrt{s}}$ is the function that depends on the duty factor s; A and B are the dimensionless coefficients which depend on the grinding scheme, for example, for the scheme of flat surface grinding by the periphery of the wheel we have: $A = -1.24$; $B = 1.62$.

For an intermittent wheel, the total number of pulses (the number of macro- or micro-cycles of intermittent grinding) in the heating time interval $0 \le \tau \le \tau_h$ can be determined by the formula

$$n = \frac{V_{cut}\sqrt{D\,t_{gr}}}{V(l_1 + l_2)}, \qquad (10)$$

where: V_{cut} is the cutting speed in the grinding, m/s; D is the grinding wheel diameter, m; t_{GR} is the depth of cut in the grinding, m; l_1 and l_2 are the cutting segment length and the groove length, respectively, m.

Applying the superposition principle for any number n of cycles of heating and (no heating, but not cooling), we obtain the following recurrent formula for determining the temperature $T(n)$ at the interval with the duration τ_h.

In Fig. 7 the following designations are made: curve 1 is that from the effect of a constant heat flux density $q(\tau) = q_{\max} =$ 40 W/mm²; curve 2 is obtained by the superposition method according to equation (10); curve 3 is the total steady-state temperature according to the model (4)-(8); 4 is the continuously increasing part of the steady-state temperature according to equation (5).

To plot the grinding temperature versus time (Fig. 7) using equations (4)-(8) and (10) in the MathCAD medium, we accept the following initial data: $D =$ 390 mm (from a possible interval of 300-400 mm), $l_1 =$ 20 mm, l_2 = 15 mm, $V_{cut} =$ 35 m/s, V = 2 m/min, $t_{gr} = 0.028$ mm, $q_{\max} = 40 \cdot 10^6$ W/m², $\lambda = 42$ W / (m · °C), $a = 8 \cdot 10^6$ m² /s. Under these conditions $l_1 + l_2$ = 35 mm, the number of cutting segments on an intermittent wheel is 35, the time of one complete revolution of the wheel is 35 ms, the exposure time of the unmoving flat heat source is $\tau_h = 100$ ms, the number of revolutions of the cycle over time τ_h is 2.9.

$$T(n) = \frac{2q_{\max}}{\lambda}\Bigg(\sum_{i=1}^{n}\sqrt{a\left[\tau-(i-1)T\right]}\cdot\operatorname{ierfc}\frac{x}{2\sqrt{a\left[\tau-(i-1)T\right]}} - \\ -\sqrt{a\left[\tau-(i-1)T-T_1\right]}\cdot\operatorname{ierfc}\frac{x}{2\sqrt{a\left[\tau-(i-1)T-T_1\right]}}\Bigg)\cdot \qquad (11)$$

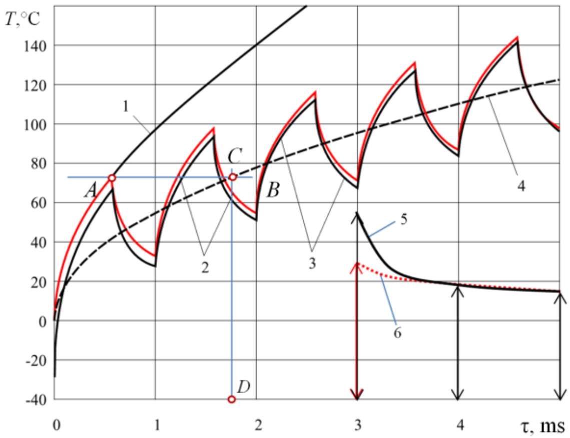


Fig. 7. **The grinding temperature at the beginning of the heating macro-cycle in the transition process lasting 5 ms (1/7 of the cycle's revolution)**

***Source*: compiled by the author**

Thus, one micro-cycle of intermittent grinding with duration of $\tau_h = 100$ ms includes 100 micro-cycles with duration of $T = 1$ms, while during one revolution of the wheel 35 grinding micro-cycles occur.

The duration of the cutting segment (ledge) with the length l_1 is

$$T_1 = \frac{l_1}{V_{кр}} = \frac{20 \cdot 10^{-3}}{35} = 0.5714 \cdot 10^{-3} \text{ s.}$$

Hence, we have $T_1 =$ 0.5714 ms.

The time of absence of a thermal pulse when a groove length with the length l_2 is passed over the contact point

$$T - T_1 = \frac{l_2}{V_{кр}} = \frac{15 \cdot 10^{-3}}{35} = 0{,}42857 \cdot 10^{-3} \text{ s.}$$

Hence, we have $T - T_1 = 0.4286$ ms.

The duty factor for periodic heat flux

$$s = \frac{T_1}{T} = \frac{0{,}5714}{1} = 0{,}5714 \, .$$

From the analysis of the data in Fig. 6) it can be seen that the mathematical model (4)-(8) gives the greatest error in the interval of the first grinding micro-cycle: the total temperature obtained by formula (2) varies from -27 ° C to +66 ° C (curve 3), while the temperature obtained by the superposition method according to formula (10) varies from 0 to +73 ° C (curve 2).

Starting from the second micro-cycle and further, the difference between graphs 2 and 3 constructed according to formulas (4)-(8) and (10), decreases. It is caused by the attenuation of the transition process of temperature change. Temperature amplitudes of the 1st, 3rd, and 5th pulses for curves 3 and 2 stop rising and stabilize according to graphs 5 and 6, respectively (Fig. 7). The continuously increasing temperature component (curve 4 in Fig. 7) is similar to exponent function; however, unlike the exponential law, it does not stabilize at a constant level, but continues to increase. Moreover, this increase occurs at a slowing rate as the duration of the grinding macro-cycle in the interval of $0 \le \tau \le \tau_h$ increases. Starting from the 5th pulse, the difference between graphs 2 and 3 (Fig. 7) can be neglected, the transition process ends, since the relative error in determining the maximum temperature does not exceed 2 %. The time of the transition process found above (empirically) corresponds to the time constant, which can be found from the following condition.

The maximum value of the amplitude of the first temperature pulse obtained by the superposition method (line *AB* in Fig. 7) is equal to a continuously increasing temperature component (the point of intersection of line AB with curve 4). The line *CD* passing through the indicated intersection cuts off the time coordinate on the abscissa equal to the time constant. This can be written as the following mathematical condition

$$\frac{2q_{\max}}{\lambda} \sqrt{\frac{aT_1}{\pi}} = \frac{2q_{\text{ave}}}{\lambda} \sqrt{\frac{a\tau_t}{\pi}} \, , \qquad (11)$$

where τ_t is the time constant of the transition process of temperature change.

Given the relationship between the parameters $q_{\max}$ and q_{ave} from (9) we obtain

$$\tau_t = \frac{T}{s} = TQ \, , \qquad (12)$$

where Q is the reciprocal of the duty factor for periodic rectangular heat flux.

For the case under consideration ($s = 0.5714$), the time constant of the transient process according to formula (10) is

$$\tau_t = \frac{1}{0{,}5714} = 1{,}75 \text{ ms.}$$

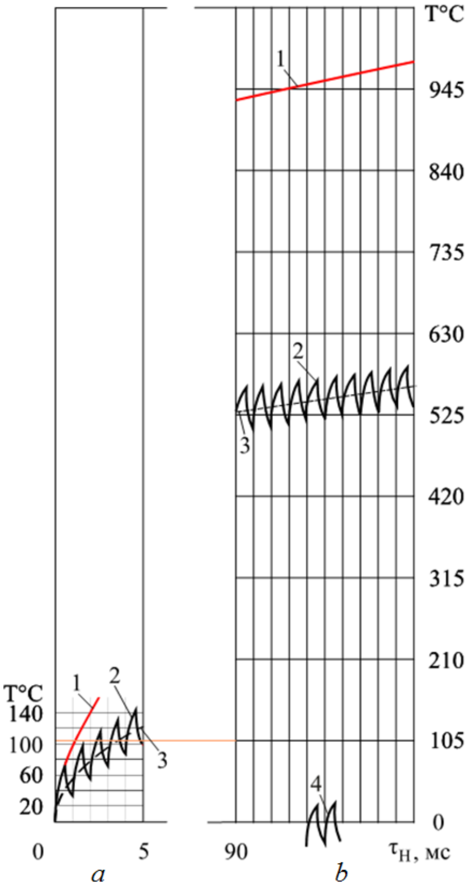


Fig. 8. **The temperature of intermittent grinding (*N* = 35) in the time interval of the transition process (*a*) and the finally established temperature (*b*)**

***Source*: compiled by the author**

It is known that the time of an exponential transition process, at which the output value takes 95 % of its steady-state value, is approximately equal to the triple value of the time constant of the change in the output value (temperature). Based on this rule, the transition process time will be $1.75 \cdot 3 = 5.25$ ms.

To verify the correct estimation of the transient constant time using the formula (12), the grinding temperature was calculated in the MatLAB program using equation (11) over the entire grinding macrocycle interval of $0 \le \tau \le \tau_h$ (Fig. 8).

In Fig. 8 the following designations are made: curve 1 is the continuously increasing temperature from the influence of the maximum heat flux $q(\tau) = q_{\max} = \text{const}$; curve 2 is the total temperature of intermittent grinding; curve 3 is the continuously increasing intermittent grinding temperature from the influence of the average heat flux $q(\tau) = q_{\text{ave}} = \frac{q_{\max} T_1}{T}$; curve 4 is the fragment of the periodic (steady-state) temperature component.

It is seen now that the intermittent grinding temperature (curve 2 in Fig. 7) can be represented by the sum of the two components: the continuously increasing component 3 and the periodic component 4.

Thus, there are three mathematical models to determine the intermittent grinding temperature, to wit: (4)-(8), (9), and (11). These models allow you to find the temperature of dry intermittent grinding, i.e. in the absence of forced cooling by grinding fluid through the slots (grooves) of the wheel.

4.2. Wet intermittent grinding model

To account for forced cooling, i.e. in the case of wet intermittent grinding, each grinding macro- or micro-cycle is proposed to be considered as consisting of two consecutive stages (heating and cooling). The temperature field at the first stage of the cycle is described by the equation

$$T_h(x,\tau) = \frac{2q_{\max}\sqrt{a\tau}}{\lambda}\,\text{ierfc}\,\frac{x}{2\sqrt{a\tau}}, \tag{13}$$

where $T_H(x,\tau)$ is the heating stage temperature depending on depth x and time τ, ºC.

The temperature field at the second stage of the macro- or micro-cycle (forced cooling) can be obtain based on the formula given in [18], i.e.

$$\begin{aligned} T_C(x,t) = {} & \int_0^\infty \left[\frac{1}{2\sqrt{\pi a t}} \left\{ \exp\left(-\frac{(x-x')^2}{4at}\right) + \exp\left(-\frac{(x+x')^2}{4at}\right) \right\} - \right. \\ & \left. - A\exp\left(atA^2 + A(x+x')\right) \times \text{erfc}\left(\frac{x+x'}{2\sqrt{at}} + A\sqrt{at}\right) \right] f(x')\,dx' + \\ & + aA\int_0^t \left[\frac{\exp\left(-\frac{x^2}{4a(t-\tau)}\right)}{\sqrt{\pi a(t-\tau)}} - A\exp\left(aA^2(t-\tau) + Ax\right)\text{erfc}\left(\frac{x}{2\sqrt{a(t-\tau)}} + A\sqrt{a(t-\tau)}\right) \right] \varphi(\tau)\,d\tau . \end{aligned} \tag{14}$$

Here

$$f(x') = \frac{2q\sqrt{at_h}}{\lambda}\left[\frac{1}{\sqrt{\pi}}\exp\left(-\frac{x'^2}{4at_h}\right) - \frac{x'}{2\sqrt{at_h}}\,\text{erfc}\left(\frac{x'}{2\sqrt{at_h}}\right)\right] + T_0 . \tag{15}$$

In formulas (14) and (15) the following designations are made: t is the current cooling time, s; $A = \frac{\alpha}{a}$ is the reduced heat transfer coefficient, J/(m^4·ºC); α is the heat transfer coefficient, W/(m^2·ºC); T_0 is the temperature of the material being ground before grinding, °C; $\varphi(\tau)$ is the initial grinding fluid temperature, which can change during the cooling time interval $0 \le \tau \le t$, °C; t_h is the heating stage time, s.

Based on measured the wheel specified geometric parameters l_1 and l_2 for wheels of monocorundum WG946Hs12Vs, sol-gel corundum 3SG46Hs12Vs, and electrocorundum A9946Hs12Vs the geometrical parameters N (number of cutting segments on the wheel) and s (duty factor) are experimentally found and given in Table 1.

In Table 1 the following designation are used: $N = 2\pi R / (l_1 + l_2)$; R is the grinding wheel radius, $R = 200$ mm; $s = l_1 / (l_1 + l_2)$.

The results of practical application of the developed mathematical software are presented in Table 2 which gives the high porous wheels geometric parameters providing a minimum grinding temperature in the interval of 577-588 °C.

Table 1. **Experimentally found parameters *N* and *s* for highly porous grinding wheels**

Wheel	N	s
WG946Hs12Vs Monocorundum	313	0,75
3SG46Hs12Vs Sol-gel corundum	292	0,64
A9946Hs12Vs Electrocorundum	288	0,68

***Source*: compiled by the author**

The results of practical application of the developed mathematical software are presented in Table 2 which gives the high porous wheels geometric parameters providing a minimum grinding temperature in the interval of 577-588 °C.

Table 2. **The high porous wheels optimum geometric parameters calculated**

Minimum temperature	Duty factor (s)		
	0.2	0.5	0.8
577 °C	$N \geq 311$	$N \geq 40$	$N \geq 7$
582 °C	$N \geq 228$	$N \geq 25$	$N \geq 5$
588 °C	$N \geq 152$	$N \geq 18$	$N \geq 3$

***Source*: compiled by the author**

From the data obtained in Table 2, a number of very important conclusions follow.

1. To ensure the same minimum temperature (for example, 577 ° C) as the duty factor decreases from 0.8 to 0.2, the number of cutting elements on the periphery of the grinding wheel increases sharply: from 7 to 311 (44.4 times). For a temperature of 588 ° C - 152: 3 = 50.7 times. That is, any interruption of the process (as compared to continuous cutting) is irrational from the point of view of the productivity of grinding stock removal (the stock is not removed in the area l_2). Therefore, an increase in the length of the area l_2 is accompanied by an increase in the “load” on the area l_1.The latter leads to an increase in grinding temperature. To reduce this temperature, it is necessary to increase (and substantially) the number of cutting segments on the periphery of the intermittent grinding wheel. In the case considered, the increasing is approximately 50 times. Such an increase is only possible with the use of the corresponding highly porous grinding wheels, for example, the wheels indicated in Table 1.

2. To reduce the temperature from 588 °C to 577 °C (by only 11 °C or 2 %), the number of cutting elements on the periphery of the grinding wheel must be doubled, regardless of the duty factor ($0.2 \leq s \leq 0.8$). For example, at $s = 0.2$ and $s = 0.8$, the value should be increased from 152 to 311 and from 3 to 7, respectively (Table 2).

3. From what has been said in paragraphs 1 and 2, it follows that the appearance of discontinuity on the grinding wheel is not in itself a panacea that prevents an increase in the grinding temperature. Within the exclusively temperature model of the process, the grinding temperature, defined by formula (11), can even increase compared to a continuous wheel, for which $s = 1$. Therefore, the observed decrease in temperature during grinding by intermittent grinding wheels, including highly porous wheels, is not caused by as much due to the lack of heating in the area, how much due to favorable conditions for chip removal (chip pockets).

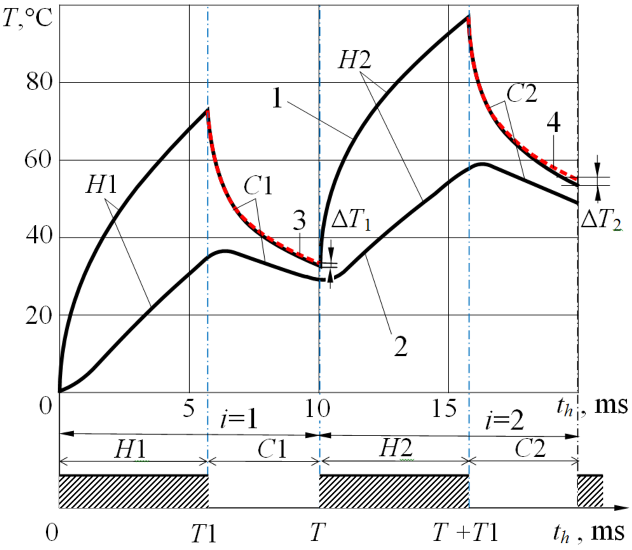


Fig. 9. **The temperature of intermittent grinding on the first two micro-cycles out of 100 available, constructed by stitching method**
***Source*: compiled by the author**

4. The temperature model obtained for the first time and represented by equations (13) and (14), additionally takes into account convective heat transfer, i.e. is adequate to wet intermittent grinding. This model showed that due to the possibility of forcing coolant pumping through the cavities (grooves and pores) of the intermittent grinding wheel, a new resource appears to reduce the temperature of intermittent grinding, which is inherent only

in the intermittent wheel. This can be seen from the analysis of the obtained mathematical dependence (14), which describes the temperature field in the cooling section, taking into account the coolant pumping through the grooves of the discontinuous wheel. The graph of intermittent grinding temperature with and without taking into account coolant pumping through the grooves or pores of the intermittent wheel under conditions of a transient temperature change (Fig. 9) indicates an additional decrease in temperature (ΔT_i) at each heat pulse with serial number $i = 1, 2, ... n$ where n is determined by the formula (10).

To build Fig. 9, calculations were performed according to equations (13) and (14) for the heating and cooling time intervals, respectively. Curves 1 and 2 in Fig. 9 show the surface temperature ($x = 0$) and at a fixed depth $x = 50$ μm, respectively. Each of these curves consists of two sections: heating ($H1$ and $H2$) and cooling ($C1$ and $C2$). The numbers 3 and 4 indicate dashed lines that correspond to the cooling areas during dry intermittent grinding, i.e. dashed lines are constructed according to equation (11). The parameters ΔT_1 and ΔT_2 (moreover, $\Delta T_1 < \Delta T_2$) correspond to an additional decrease in temperatures caused by convective heat transfer on the first two grinding microcycles. Further, these increments accumulate, which leads to an additional decrease in the total temperature of intermittent grinding during forced cooling.

Therefore, by controlling the temperature, i.e. $\varphi(\tau)$ in formula (14), and cooling, i.e. α in formula (14) properties of the coolant, it is possible to further reduce the temperature in the cutting zone during intermittent grinding. This opens up new possibilities both in the technology of grinding with intermittent and highly porous grinding wheels, and in the design of these wheels for effective abrasive processing. Some related additional issues are discussed in the works [19-20].

5. CONCLUSIONS

1. A unified classification of intermittent grinding wheels has been developed based on the frequency of impact of the cutting sections of the wheel on the surface being ground (determined by number of cutting sections on the wheel), as well as taking into account the duty factor of the period of heat flux pulses.

2. A set of the wheel geometric parameters is proposed for designing optimal constructions of discontinuous grinding wheels including segmented, slotted, and high porous wheels, to wit: number of cutting sections on the working periphery of the grinding wheel and the duty factor of the period of heat flux pulses. A technique has been developed for determining the geometric parameters of high porous grinding wheels by the criterion for the ratio of sizes of the cutting section and pore.

3. The temperature field during dry intermittent grinding is the result of the cyclic effect of the pulsed heat flux on the surface being ground and is determined by the superposition of the temperature fields formed at the heating and cooling stages when the cooling means no heating. For forced cooling with grinding fluid through the slots (grooves) of the intermittent grinding wheel, the initial condition for determining the temperature field at the stage of forced cooling is the changing temperature field caused by the heat flux at the heating stage. Thus, the wet intermittent grinding temperature field is also formed by special form summing (stitching) the temperature fields.

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МОДЕЛЮВАННЯ ТЕМПЕРАТУРИ ПЕРЕРИВЧАСТОГО ШЛІФУВАННЯ ДЛЯ МОНІТОРИНГУ СТАНУ ТЕХНОЛОГІЧНОЇ СИСТЕМИ

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АНОТАЦІЯ

Розроблено та досліджено математичну модель для визначення температури переривчастого шліфування насухо і з примусовим охолодженням на інтервалах часу теплового макро- і мікроциклів. Стадія нагріву відповідає часу проходження ріжучого сегмента шліфувального круга через кожну точку зони контакту. Стадія охолодження відповідає часу проходження канавки (або пори) шліфувального круга через зазначену точку. Температурне поле переривчастого сухого шліфування формується накладенням температурного поля на зазначених стадіях циклу нагріву і охолодження від впливу теплового потоку в кожній точці поверхні, що шліфується. У той же час при переривчастому шліфуванні зі шліфувальної рідиною через канавки (або пори) переривчастого шліфувального круга температурне поле, сформоване на стадії нагріву, є початковою умовою для визначення температурного поля на стадії примусового охолодження. На основі отриманої моделі температурного поля при переривчастому шліфуванні, такі геометричні параметри переривчастого (щілинного, сегментованого і високопористого) шліфувального круга знайдені і визначені: кількість ріжучих сегментів на крузі і коефіцієнт заповнення періоду теплових імпульсів, що дорівнює відношенню довжини ріжучого виступу до суми довжин ріжучого виступу і западини. Температурне поле переривчастого шліфування з примусовим охолодженням сформовано методом припасування (зшивання) полів температури на ділянках нагріву і охолодження. При цьому теплообмін поверхні, що шліфується з охолоджуючим середовищем, яка періодично діє на цю поверхню під час стадії охолодження, враховується в кожному макро- і мікроциклі дії теплового потоку при переривчастому шліфуванні, що дозволяє додатково знизити температуру в зоні шліфування. Представлена стаття є результатом поточної роботи, виконаної в рамках наукової школи професора О.В. Якимова - основоположника технології переривчастого шліфування і автоматизації шліфувальних операцій.

Ключові слова: шліфування всуху; примусове охолодження; щілинні і сегментовані круги; високопористі круги; ріжучий сегмент; не ріжуча ділянка

Статья посвящается 95-летию со дня рождения профессора А.В. Якимова
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МОДЕЛИРОВАНИЕ ТЕМПЕРАТУРЫ ПРЕРЫВИСТОГО ШЛИФОВАНИЯ ДЛЯ МОНИТОРИНГА СОСТОЯНИЯ ТЕХНОЛОГИЧЕСКОЙ СИСТЕМЫ

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АННОТАЦИЯ

Разработана и исследована математическая модель для определения температуры прерывистого шлифования всухую и с принудительным охлаждением на интервалах времени теплового макро- и микроциклов. Стадия нагрева соответствует времени прохождения режущего сегмента шлифовального круга через каждую точку зоны контакта. Стадия охлаждения соответствует времени прохождения канавки (или поры) шлифовального круга через указанную точку. Температурное поле прерывистого сухого шлифования формируется наложением температурного поля на указанных стадиях цикла нагрева и охлаждения от воздействия теплового потока в каждой точке шлифуемой поверхности. В то же время при прерывистом шлифовании со шлифовальной жидкостью через канавки (или поры) прерывистого шлифовального круга температурное поле, сформированное на стадии нагрева, является начальным условием для определения температурного поля на стадии принудительного охлаждения. На основе полученной модели температурного поля при прерывистом шлифовании, следующие геометрические параметры прерывистого (щелевого, сегментированного и высокопористого) шлифовального круга найдены и определены: количество режущих сегментов на круге и коэффициент заполнения периода тепловых импульсов, равный отношению длины режущего выступа к сумме длин режущего выступа и впадины. Температурное поле прерывистого шлифования с принудительным охлаждением сформировано методом припасовывания (сшивания) полей температуры на участках нагрева и охлаждения. При этом теплообмен шлифуемой поверхности с охлаждающей средой, которая периодически действует на эту поверхность во время стадии охлаждения, учитывается в каждом макро- и микроцикле действия теплового потока при прерывистом шлифовании, что позволяет дополнительно снизить температуру в зоне шлифования. Представленная статья является результатом текущей работы, выполненной в рамках научной школы профессора А.В. Якимова – основоположника технологии прерывистого шлифования и автоматизации шлифовальных операций.

Ключевые слова: шлифование всухую; принудительное охлаждение; щелевые и сегментированные круги; высокопористые круги; режущий сегмент; не режущий участок

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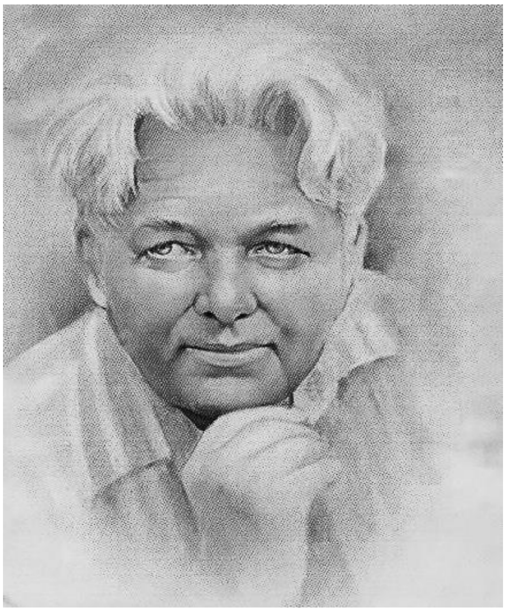
This article is dedicated to the 95th birthday of Professor A.V. Yakimov (born March 16, 1925)

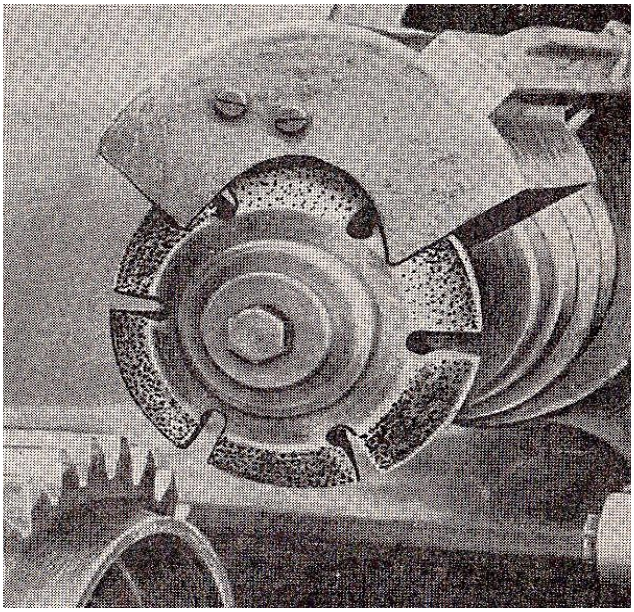
Professor Alexander Yakimov and his Scientific School

Professor A. V. Yakimov is a well-known scientist and a major specialist in mechanical engineering technology, the organizer of a scientific school and the founder of the teachings on the finishing methods of diamond-abrasive machining of machine parts made from construction steels, metals and alloys, including hard-to-work materials and materials which is prone to the formation of grinding defects such as burns and microcracks. Standing at the origins of the scientific directions created by himself, he prepared a galaxy of scientists and like-minded people who successfully work not only in Ukraine but also in other countries of the near and far abroad, including Germany and the USA.

In 1956 he defended his thesis on the topic “Study of the rigidity of metal-cutting machines such as MAAG”. After graduating from graduate school in 1956, he was sent to work and began his academic career at the Zaporizhia machine construction institute, where he first worked as a senior lecturer (from 1956 to 1958) and part-time as deputy dean of the mechanical-and-technological faculty, and then as an assistant professor at the department of “Metal-cutting machines and tools”. In 1961, by competition, he joined the Perm polytechnic institute, first as an assistant professor of the department “Metal-cutting machines and tools” (1961-1963) and part-time as the dean of mechanical-and-technological faculty, and then (from 1963 to 1974) as head of the “Manufacturing technology” department. Working as the head of the department, A. V. Yakimov was able to combine the scientific interests of his department with that of the departments of “Physics”, “Automation and telemechanics”, as well as “Metal science and heat treatment”, “Strength of materials”, “Metal-cutting machines and tools”. This creative association made it possible, on the one hand, to increase the scientific and theoretical level of work performed for industry, and, on the other hand, to create conditions for the growth of personnel. So in 1963, the dissertation was defended on thermal processes during grinding by the head of the Department of “Physics” V. A. Sypailov, who in 1973 successfully defended his doctoral dissertation on the subject “Fundamentals of the theory of thermal processes in the grinding of metals”. So, under the leadership of A.V. Yakimov a scientific school begins to form on thermal phenomena during grinding and quality management of the surface layer of machine parts.



Alexander Yakimov 1925–2016



Intermittent gear grinding

It should be noted here that for decades scientists have struggled to solve the problem of controlling the quality of the surface layer of machine parts during grinding. Up to 35-40% of expensive parts with high accuracy after grinding, went into an unrecoverable scrap. The reason was burns and microcracks hidden from the eyes that occur during grinding workpieces of metals and alloys with abrasive tools under the influence of high temperatures in the cutting zone. Multimillion-dollar losses were perceived as an inevitable evil. Even the selection of grinding understated parameters, so-called "gentle" grinding modes, which several times reduce the grinding performance, did not completely eliminate grinding defects. As a result, the durability of bearings decreased by 3 times, of gears – by 5-8 times, of blanking or cutoff dies – by 30 times.

A systematic approach to solving a complex problem made it possible in those years to make a breakthrough in the technology of grinding critical machine parts and formulate the main directions for the automation of grinding machines and the technology of manufacturing abrasive tools. The problem was solved by the A. V. Yakimov's method of intermittent grinding, which was proposed by a group of scientists under the leadership of the head of the department of "Manufacturing technology" A. V. Yakimov.

The essence of the intermittent grinding method can be understood by comparing the time of thermal saturation (the time during which the grinding temperature reaches a steady-state value) with the time of action of the heat source in the contact zone between a grinding wheel and a workpiece. Since the indicated time intervals are comparable in magnitude, it becomes possible to control the intermittent grinding temperature adjusting the number and size of the cutting segments on an abrasive or diamond grinding wheel. The innovative technological idea of intermittent grinding formed the basis of the A.V. Yakimov's doctoral dissertation, which he defends in 1970 at the Moscow aviation institute on the topic "Technological basis of the grinding process with wheels that have an intermittent working surface". In 1972, he was awarded the academic title of professor.

Since 1974, the scientific and pedagogical activity of Professor A. V. Yakimov continues at the Odessa polytechnic institute (now Odessa national polytechnic university), where he was invited by competition to the post of head of the department of "Manufacturing technology" and where he continues to successfully lead the scientific school he created. Developing the ideas of his doctoral dissertation, Professor A. V. Yakimov successfully led both graduate and doctoral students who comprehensively studied various aspects of intermittent grinding technology, and also developed methods for automatically controlling the quality of the surface layer of critical machine parts during their finishing. In these areas, dozens of candidate and doctoral dissertations are defended.

In the 70s and 80s, the design of new diamond wheels constructions was carried out at the Institute of Superhard Materials of the Academy of Sciences of the Ukrainian SSR under the leadership of Professor A. V. Yakimov. This gave the discontinuous grinding process a new impetus for further development, which was accompanied by the widespread introduction of intermittent diamond grinding wheels.

It turned out that in addition to reducing temperature and increasing the cutting ability of intermittent diamond wheels, the method of intermittent diamond grinding allows you to significantly save expensive rough diamonds, i.e., natural and artificial diamonds. For example, in the manufacture of intermittent diamond wheels, the same amount of rough diamond allows one to produce a larger number of diamond intermittent (i.e., discontinuous) wheels on its basis (in comparison with similar continuous wheels). The successful introduction of intermittent diamond wheels in numerous aircraft, engine and machine-tool factories served as a convincing justification for the assignment to Professor A. V. Yakimov honorary titles of Honored Worker of Science and Technology of Ukraine (1982) and Laureate of the State Prize of Ukraine (1986).

The Odessa Polytechnic Institute (now ONPU) finally formed two main areas of research work on the management of abrasive-diamond machining, to wit:

(1) introducing into the grinding system of new structural and technological elements (intermittent grinding, elastic-damping fastening of the wheel, new dressing technologies for grinding wheels, cutting and grinding lubricating compounds);

(2) automatic (adaptive, intelligent, computer) control of the process of diamond-abrasive processing based on the use of information that occurs during processing. In the first case, the control is open, i.e., without using feedback on the technological parameters, in the second – closed one when the correction of the machining process is carried out using the feedback circuit. In both of these areas, under the leadership of Professor A. V. Yakimov the candidate dissertations are being carried out, including the generalizing doctoral work of the author of these lines V. P. Larshin, combining both these areas into a single integrated grinding system, which takes into account a single mechanism of production and its preparation. It was found that due to general (as opposed to partial) optimization, the efficiency of integrated systems is higher than the effectiveness of separate design and machining systems. A new approach to design and production automation corresponded to a promising direction in manufacturing technology – the development of integrated production systems. In foreign literature such systems are called “Computer-Integrated Manufacturing Systems” based on the comprehensive use of computer technology, both in the preparatory and executive phases of the production process. The practical implementation of this campaign was facilitated by the rapid pace of development of hardware and software for computerized CNC systems with an open architecture. Currently, integrated production systems have been further developed in the form of CALS technologies (Continuous Acquisition and Life Cycle Support), i.e., continuous information support for the product life cycle).

In 1998, Professor A. V. Yakimov becomes a full member of the Engineering Academy of Ukraine. By this time he was the author of numerous monographs, manuals and textbooks. His participation in the work of the Engineering Academy of Ukraine leads to the emergence of another area of scientific and educational activities of Professor A. V. Yakimov, to wit: organization and holding in Ukraine of large international conferences on the subject of physical and computer technologies in mechanical engineering. Such conferences, chaired by Professor A. V. Yakimov, become annual (and even twice a year) holding in Kharkov on the basis of the Kharkov State Enterprise “FED”. The proceedings of these conferences contain detailed materials on modern technological research and development, including questions of information and methodological support of the educational process. They were published in the form of special issues: “News of the Academy of Engineering of Ukraine”, “The Herald of the Kharkiv State Technical University of Agriculture”, as well as in the form of separate works of the indicated international conference. Participation in the conference of famous scientific schools provided an opportunity to combine creative efforts, which was reflected in the decision to prepare 10-volume publication of materials on modern trends in the development of manufacturing technology. The last 10th volume was published in 2005. Professor A. V. Yakimov prepared 55 candidates and 6 doctors of technical sciences. His students continue to develop the ideas of their teacher. Among them are famous scientists and educators. They all adhere to a single scientific direction – improving the technology of metal cutting and abrasive-diamond machining, have a joint interest in the development of scientific research, training and preparing young researchers: masters, graduate and doctoral students. Many students of Professor A. V. Yakimov occupy senior positions in industry. Creative work in the scientific school of Professor A.V. Yakimov is based on the continuity of decisions, which consists in the fact that new solutions use previous developments, which is tested by laboratory and factory practice. The characteristic features of the scientific school of Professor A. V. Yakimov are the friendly atmosphere in the creative team and the inextricable connection of scientific research with industry and the educational process at the university. This allows significantly improving the quality of training of young specialists, to eliminate the well-known contradiction between the development of new advanced technologies and the production where these technologies are introduced.

The results of long scientific research and experiments Professor A. V. Yakimov outlined in a large number of scientific and educational works. There are more than 300 of these works, including more than 80 inventions, more than 15 study guides and textbooks. Among major works, one can note, for example, the monographs: “Intermittent grinding”, “Optimization of the grinding process”, “Abrasive-diamond machining of profile surfaces”, “Quality of manufacturing gears”, etc. In addition, under his editorship, there were published for example, such textbooks as: “Automated Engineering Technology”, “Grinding Process Management”, “Optimization of Technological Processes in Mechanical Engineering”, “Fundamentals of Thermal

Phenomena in Grinding Machine Parts", etc. In 2012, another textbook "Manufacturing Technology" was published under the general editorship of Professor A. V. Yakimov.

Scientific school of Professor A. V. Yakimov continues to work successfully. In recent years, research has been carried out on the analysis and synthesis of technological processes and systems for metal cutting and abrasive machining for complex-profile parts from difficult-to-machine materials. These are alloyed, heat-resistant and stainless steels, titanium and titanium alloys, polymeric and composite materials. For example, lead ball screws for machine tools and aircrafts, gears for conveyor gear boxes, as well as aviation and automobile gears. Fundamental theoretical developments are being carried out on grinding thermophysics and cutting dynamics in order to optimize technological systems based on the study of thermodynamic processes occurring in the contact zone of the grinding wheel and vibrations in the elastic system of CNC machines. Theoretical studies are carried out on the general theory of intermittent grinding including conventional, macro- and micro-intermittent grinding taking into account forced cooling. These developments are necessary to create new, more advanced methods of metal cutting and abrasive machining, including grinding with highly porous (micro-intermittent) wheels, machining using new compositions and methods for supplying solid metal cutting lubricants, and the use of technological diagnostics and adaptive control systems for CNC machines.

In 2018, another doctoral dissertation was defended by Lishchenko, N. V. on the topic "Profile grinding productivity increasing on CNC machines on the basis of grinding system elements adaptation". The dissertation is devoted to solving an important scientific and technical problem of increasing the productivity of defect-free profile gear grinding on CNC machines on the basis of the development of appropriate technological preconditions and subsystems for the designing, monitoring and diagnosing of the operation, which allow adapting the elements of the grinding system to higher productivity. For this purpose a methodology is developed for researching the profile grinding system using scientific methods of modeling, optimization and control, as well as corresponding technology preconditions in the form of a set of purposeful methods and means of innovative profile grinding technology, to wit: grinding stock mathematical models for the transformation of the grinding stock uncertainty into the taking grinding wheel away from a gear to be grinded, method of the grinding stock aligning on the gear periphery without making corrections in its angular position, method of a profile grinding wheel adaptive dressing, etc. The software for these subsystems is created on the basis of the mathematical models of the temperature field with and without taking into account the effect of forced cooling. The technological superiority of high-porosity (micro-intermittent) grinding wheel has been theoretically demonstrated and practically confirmed in comparison with slotted (macro-intermittent) wheel. Complex of experimental research and factory tests is performed for confirming the effectiveness of the methods and means developed.

On behalf of the authors,
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