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Simplified Grinding Temperature Model Study

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Abstract. A study of a simplified mathematical model for determining the grinding temperature is performed. According to the obtained results, the equations of this model differ slightly from the corresponding more exact solution of the one-dimensional differential equation of heat conduction under the boundary conditions of the second kind. The model under study is represented by a system of two equations that describe the grinding temperature at the heating and cooling stages without the use of forced cooling. The scope of the studied model corresponds to the modern technological operations of grinding on CNC machines for conditions where the numerical value of the Peclet number is more than 4. This, in turn, corresponds to the Jaeger criterion for the so-called fast-moving heat source, for which the operation parameter of the workpiece velocity may be equivalently (in temperature) replaced by the action time of the heat source. This makes it possible to use a simpler solution of the one-dimensional differential equation of heat conduction at the boundary conditions of the second kind (one-dimensional analytical model) instead of a similar solution of the two-dimensional one with a slight deviation of the grinding temperature calculation result. It is established that the proposed simplified mathematical expression for determining the grinding temperature differs from the more accurate one-dimensional analytical solution by no more than 11 % and 15 % at the stages of heating and cooling, respectively. Comparison of the data on the grinding temperature change according to the conventional and developed equations has shown that these equations are close and have two points of coincidence: on the surface and at the depth of approximately threefold decrease in temperature. It is also established that the nature of the ratio between the scales of change of the Peclet number 0.09 and 9 and the grinding temperature depth 1 and 10 is of 100 to 10. Additionally, another unusual mechanism is revealed for both compared equations: a higher temperature at the surface is accompanied by a lower temperature at the depth.

Keywords: grinding temperature, heating stage, cooling stage, dimensionless temperature, temperature model.

1 Introduction

Abrasive machining works by forcing the abrasive particles, or grains, into the surface of the workpiece so that each particle cuts away a small bit of material. Abrasive machining is similar to conventional machining (metal cutting), such as milling or turning, because each of the abrasive particles acts like a miniature cutting tool. However, unlike conventional machining, the grains are much smaller than a cutting tool, and the geometry and orientation of individual grains are not well defined. As a result, abrasive machining is less power efficient and generates more heat. The grain size may be different based on the machining. For rough grinding, coarse abrasives are used. For fine grinding, fine grains (abrasives) are used.

Abrasive machining processes can be divided into two categories based on how the grains are applied to the workpiece.

In bonded abrasive processes, the particles are held together within a matrix, and their combined shape determines the geometry of the finished workpiece. For example, in grinding the particles are bonded together in a wheel. As the grinding wheel is fed into the part, its shape is transferred onto the workpiece.

In loose abrasive processes, there is no structure connecting the grains. They may be applied without lubrication as a dry powder, or they may be mixed with a lubricant to form a slurry. Since the grains can move independently, they must be forced into the workpiece with another object like a polishing cloth or a lapping plate.

Common abrasive processes are listed below. Fixed (bonded) abrasive processes: grinding, honing, superfinishing, tape finishing, abrasive belt machining, abrasive sawing, diamond wire cutting, wire saw sanding.

Loose abrasive processes: polishing, lapping, abrasive flow machining (AFM), hydro-erosive grinding, water-jet cutting, abrasive blasting mass finishing, tumbling, open barrel tumbling, vibratory bowl tumbling, centrifugal disc tumbling, centrifugal barrel tumbling.

Grinding is an abrasive machining process that uses a grinding wheel as the cutting tool. Grinding practice is a large and diverse area of manufacturing and tool making. It can produce very fine finishes and very accurate dimensions. At the same time, in mass production, it can also rough out large volumes of metal quite rapidly. It is usually better suited to the machining of very hard materials than is "regular" machining (that is, cutting larger chips with cutting tools such as tool bits or milling cutters), and until recent decades it was the only practical way to machine such materials as hardened steels. Compared to “regular” machining, it is usually better suited to taking very shallow cuts, such as reducing a shaft’s diameter by half a thousandth of an inch or 12.7 μm.

Grinding is a subset of cutting, as grinding is a true metal-cutting process. Each grain of abrasive functions as a microscopic single-point cutting edge (although of high negative rake angle) and shears a tiny chip that is analogous to what would conventionally be called a “cut” chip (turning, milling, drilling, tapping, etc.). However, among people who work in the machining fields, the term cutting is often understood to refer to the macroscopic cutting operations, and grinding is often mentally categorized as a "separate" process (abrasive machining). This is why the terms (“grinding” and “metal cutting”) are usually used separately in shop-floor practice.

The designing, monitoring and diagnosing computer subsystems are widely used on CNC grinding machines to adapt the grinding system to higher throughput. Abrasive machining compared with metal cutting is more labor-intensive and costly. That is why the grinding system study is caused by the search for ways to improve the productivity of man and machine [1]. In this connection, there is some modern knowledge to boost the grinding system throughput. This knowledge is more important with automated computer-controlled systems than it has ever been before because quantitative knowledge is needed to design and operate these systems [2].

By means of electrical signals from sensors, you can judge the state of the machine under control and the environment. Therefore, the more sensors used, the more information you can be obtained about the grinding system and environment. However, it should be borne in mind that in real conditions there is such information which is impossible directly to take off with the help of sensors.

This situation may occur, for example, when the measured signal is distorted by noise or the controlled value cannot be converted to an electrical signal as well as when due to cost or spatial constraints you cannot use the required sensor. If in such cases the noise properties or dynamic characteristics of the object, which are held observations, are known then with the help of appropriate calculations you can evaluate the signal you are interested in [3].

This situation fully applies to the grinding temperature signal in the grinding zone which is located between a grinding wheel and a workpiece to be ground. For this reason, the development of an acceptable mathematical model for determining the grinding temperature is an urgent task in the grinding technology on CNC machines. In terms of metrology, such solution to the problem is an example of indirect measurement. This opens the way to building “hierarchically intelligent control systems” developed by Sarid is on the basis of his principle of “increasing precision with decreasing intelligence” [4]. All this mentioned above ultimately predetermines the development of the main industries in developed countries [5] and corresponds to the so-called tendency of “sustainable development”.

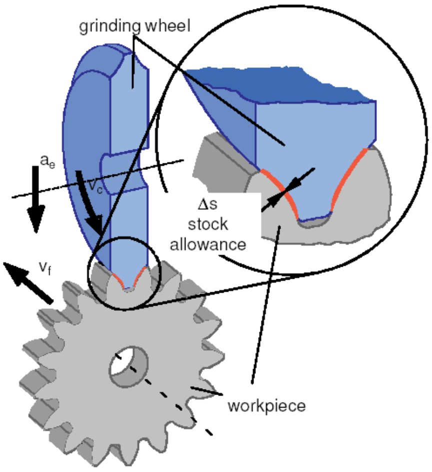
2 Literature Review

The state of the problem in the field of the grinding thermo-physical theory can be considered taking into account the following philosophical technical concepts that predetermine the corresponding particular approaches to the problem solution. Firstly, it is the concept of dry and wet grinding, which predetermines the absence or accounting of convective heat transfer under the action of grinding fluid. Secondly, it is the concept of macro- and micro-grinding, which allows considering integral (due to averaging) or local heat fluxes with and without taking into account the effect on temperature of instantaneous cutting elements – sections of abrasive grains separated by pores of the grinding wheel (highly porous grinding wheels) as well as their accidental impact on the surface being ground. This concept involves the separation of the grinding process into categories of continuous and discontinuous (with pulsed heat flux), including the grinding with and without convective heat transfer. Thirdly, the concept of super-micro-grinding, which involves taking into account the effect of individual cutting grains of the grinding wheel, with and without taking into account convective heat transfer. The first concept most closely corresponds to the theory of the Jaeger moving heat source [6, 7], on the basis of which simplified formulas for determining the maximum grinding temperature are given in a number of sources without corresponding justifications [8–10].

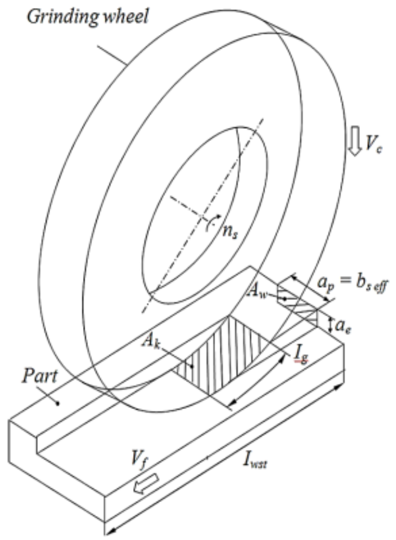
3 Research Methodology

3.1 Mathematical model

In the grinding theory, the contact spot is usually considered as a certain zone on the surface to be ground, which belongs to both the grinding wheel and the workpiece (Figure 1).



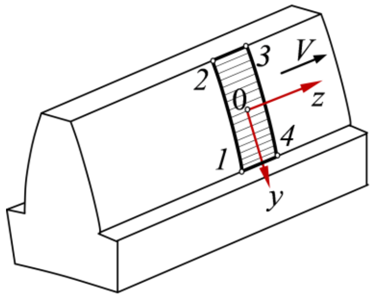
a



b

Figure 1 – Schemes of profile gear grinding (a) and flat grinding (b) with the discrete radial feed a_e of the grinding wheel to the workpiece

From the grinding thermal physics point of view, these schemes can be converted into the so-called moving heat source, indicated by the numbers 1234 in Figure 2.



a

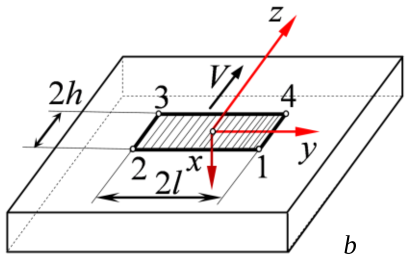


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Figure 2 – Real (a) and equivalent (b) schemes of thermal sources

It was previously established the general view of the grinding temperature equations for research: three-, two-, and one-dimension ones [11, 12]. These equations are used when the Peclet number $H = \frac{Vh}{2a}$ is more than 4, i. e. $H \geq 4$. It is assumed here that a band heat source with the width of $2h$ moves over the flat surface of a semi-infinite body along and in the positive direction of the z-axis and is infinitely long in the direction of the y-axis (Figure 2). The heat flux density q (in W/m^2) over the entire surface of the moving contact is uniform, i. e. $q = \text{const}$. The coordinate system is referenced to the moving heat source. The transition from the two-dimensional thermophysical scheme with a moving heat source to the corresponding one-dimensional schemes with unlimited and limited unmoving flat sources is performed by replacing the velocity parameter V of the heat source (in m/s) by the time τ_H of its action. For these conditions, we have the following general view of the equations for research. Firstly, we have the basic grinding temperature equation at the stages of heating (with the index "*H*") and cooling (with the index "*C*"):

$$\Theta_H(X, H) = 2\pi\sqrt{H}\,\text{ierfc}\frac{X}{2\sqrt{H}},\ 0 \leq H \leq H_H, \quad (1)$$

$$\Theta_C(X, H, H_H) = 2\pi \times$$

$$\times\left[\sqrt{H}\,\text{ierfc}\frac{X}{2\sqrt{H}} - \sqrt{H - H_H}\,\text{ierfc}\left(\frac{X}{2\sqrt{H - H_H}}\right)\right], \quad (2)$$

$$H_H < H.$$

Secondly, we have the simplified equation (obtained in the previous paper) at the stages of heating (3) and cooling (4):

$$\Theta_H^*(X,H) = 2\pi\sqrt{H}\,\frac{1}{\sqrt{\pi}}10^{-\left(\frac{X}{2\sqrt{H}}\right)},\ 0 \le H \le H_H\,, \quad (3)$$

$$\Theta_C^*(X,H) = 2\sqrt{\pi}\times$$
$$\times\left[\sqrt{H}\,10^{-\left(\frac{X}{2\sqrt{H}}\right)} - \sqrt{H-H_H}\,10^{-\left(\frac{X}{2\sqrt{H-H_H}}\right)}\right], \quad (4)$$

$$H_H < H.$$

From equations (1) and (3), we can find that the maximum dimensionless surface temperatures (i. e. at $X = 0$) according to these equations are the same (they are equal to each other). They correspond to the action time of the moving heat source which is equal to $\tau_H = 2h_H / V$ (Figure 2). That is

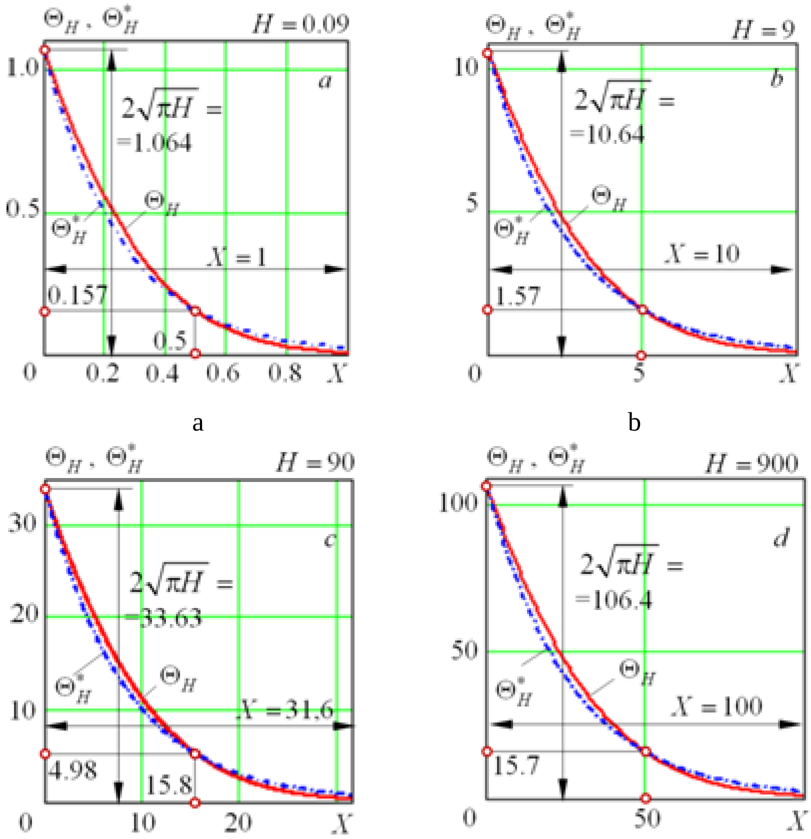
$$\Theta_{H\max} = \Theta_{H\max}^* = 2\pi\sqrt{H}\left(\frac{1}{\sqrt{\pi}}\right) = 2\sqrt{\pi H}\,. \quad (5)$$

3.2 Error in calculating the grinding temperature

The dependences of the change in the dimensionless temperature over the depth of the subsurface layer, including the surface at $X = 0$ for $H = 0.09$ (Fig. 3, *a*), $H = 9$ (Figure 3 b), $H = 90$ (Figure 3 c) and $H = 900$ (Figure 3 d) are studied.

Data in Figure 3 allows estimating practical change intervals of dimensionless variables H, X and $X/(2H^{1/2})$, which, first, correspond to a change range of regime parameters for conventional operations of flat, round and profile grinding, and secondly, at which there is a dimensionless temperature field at the heating stage (Table 1).

It can be seen (Figure 3) that the error of the simplified equation (3) compared to the original equation (1) in the zone of a ten-fold temperature drop is alternating (first lowering the temperature, then its overestimation) and the lowest errors occur at high and medium temperatures. This is just in the region of significant temperature values that affect the nature and depth of the defective layer during grinding.



a b

c d

Figure 3 – The dimensionless temperatures $\Theta_H(X,H)$ and $\Theta_H^*(X,H)$ changes at the heating stage vs depth of the subsurface layer X in a range of 0–1 (a), 0–5 (b), 0–30 (c), and 0–100 (d)

Table 1 – Formal and real intervals of changing the dimensionless parameters at the heating stage at the heating stage

Formal interval	Real interval
$0 \le X \le 41.7$	$0 \le X \le 14$
$0.047 \le H \le 104.063$	$4 \le H \le 20$
$0 \le \dfrac{X}{2\sqrt{H}} \le 96$	$0 \le \dfrac{X}{2\sqrt{H}} \le 1$

3.3 Comparing the models

To estimate the errors of the simplified dependencies (3) and (4) obtained, it is necessary to compare them with the similar more exact dependencies (1) and (2) at the heating and cooling time intervals, which were choose the same. Expressed through a dimensionless parameter H (Peclet number), the interval of dimensionless heating time for a wide range of grinding modes is $0 \le H \le 100$.

The study will be carried out, for example, in the most unfavorable case with $H = 0.09$, since for $H = 4$ the coincidence of the two-dimensional solution with the one-dimensional solution by equations (1) and (2) is most pronounced [11–14]. As an example in Figure 4 shows graphs of the change in the dimensionless grinding temperature at $H = 0.09$, constructed from equation (2), that is, in the cooling stage.

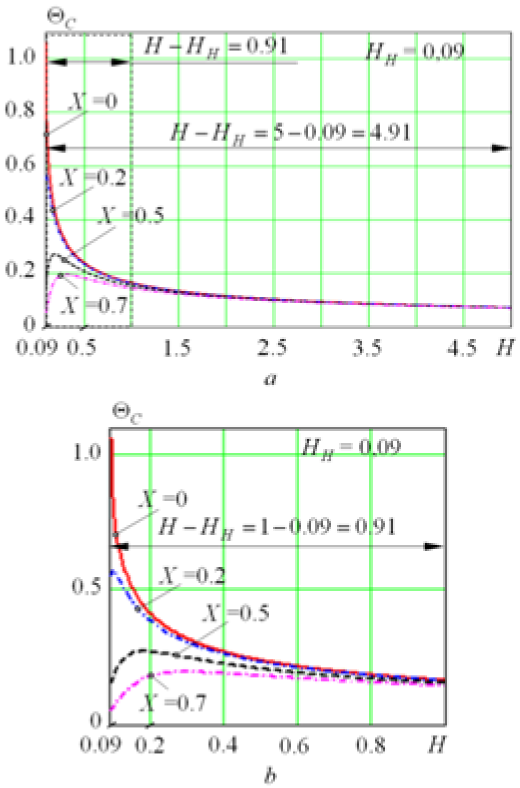


Figure 4 – The change in the dimensionless grinding temperature $\Theta_C = \Theta_C(X, H, H_H)$ according to equation (21) at the cooling stage depending on the Peclet number H at fixed distances from the surface X at $H_H = 0.09$ in the intervals $0 \le H \le 5$ (a) and $0 \le H \le 1$ (b)

It can be seen in Figure 4 that a change of H_H from $H_H = 9$ to $H_H = 0.09$ (a hundred times) leads to an increase in the scale of the dimensionless cooling time by ten times, i. e. just as it was noted in Figure 5.

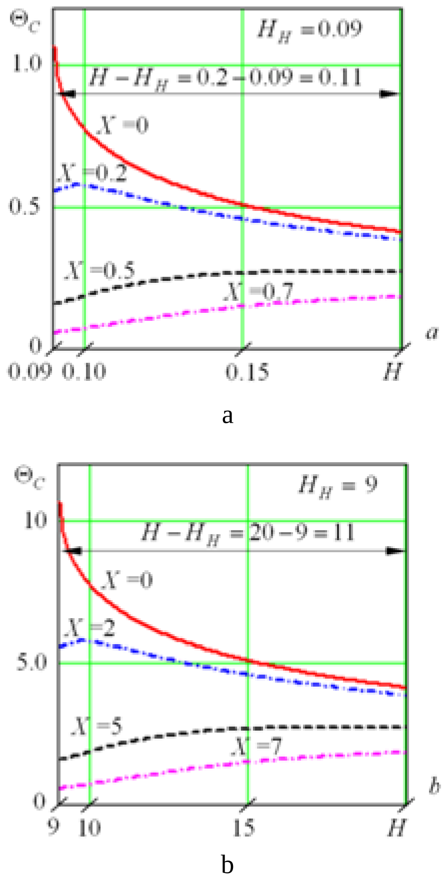
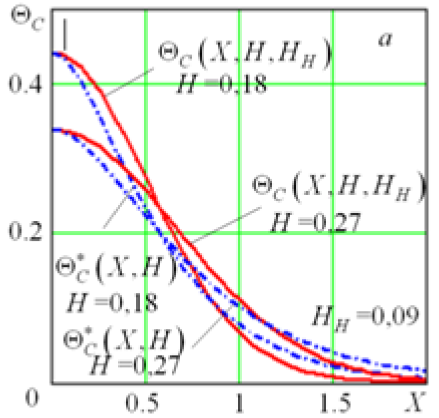


Figure 5 – The change in the dimensionless temperature depending on the Peclet number H at the cooling stage (without cooling liquid) at fixed distances from the surface X at $H_H = 0.09$ (a) and $H_H = 9$ (b)

Comparison of the data on the grinding temperature change by equations (2) and (4) is shown graphically in Figure 5. It can be seen that, as at the heating stage, equations (2) and (4) are close and have two points of coincidence: at 0 (i.e. on the surface) and at the depth of approximately threefold decrease in temperature. You can also see that the nature of the ratio between the scales of change of the H_H (0.09 and 9) and the X (1 and 10) is of 100 (9/0.09) to 10 (10/1).

In addition, another unusual mechanism is revealed for both compared equations: a higher temperature at the surface is accompanied by a lower temperature at the depth (Figure 6).



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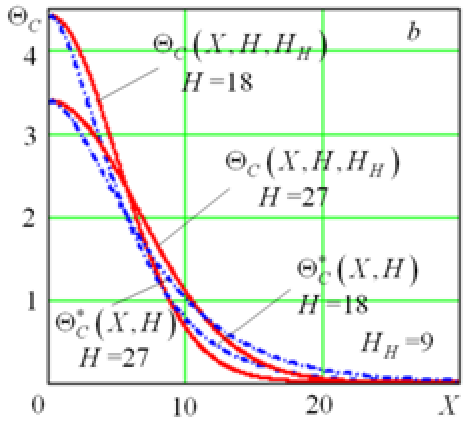

b

Figure 6 – The change in dimensionless temperature depending on the dimensionless depth X in the cooling stage (without a cooling liquid) for $H_H = 0.09$ at H = 0.18 and H = 0.27 (a), and for $H_H = 9$ at H = 18 and H = 27 (b)

The areas of use of the approximate expressions (3) and (4) are determined by comparing them with the corresponding more exact expressions (1) and (2). To do this, we limit the allowable amount of error between the compared expressions, for example, by the levels δ_H = 11 % at the heating stage and δ_C = 15 % at the cooling stage (Table 2).

Table 2 – Allowable intervals for changing the dimensionless parameters X and H

H	Heating stage	Cooling stage
0.09	$0 \le X \le 0{,}6$	$0 \le X \le 1$
20	$0 \le X \le 8{,}5$	$0 \le X \le 15$
100	$0 \le X \le 19{,}5$	$0 \le X \le 33$

The data given in Table 2 do not contradict the previously found area of their change (see Table 1). It can be seen in Table 1 that the obtained expressions (3) and (4) can be used in fairly wide intervals of X and H variation to estimate the grinding temperature and its distribution over the depth of the surface layer.

4 Conclusions

Temperatures Θ_H and Θ^*_H as well as the depth X of the fixed temperature penetration, under otherwise equal conditions, are proportional to the square root of the Peclet number. The coordinates of the same point of the previous (i-1)-th solutions $\Theta(X_{i-1}, H_{i-1})$ and $\Theta^*(X_{i-1}, H_{i-1})$ with the subsequent i-th solutions $\Theta(X_{i-1}, H_{i-1})$ and $\Theta^*(X_{i-1}, H_{i-1})$ are the same and differ in the $\sqrt{H_i / H_{i-1}}$ times. For example, when going from $H_{i-1} = 0.09$ to $H_i = 9$, the coordinate of the coincidence points on the ordinate axis changes from 1.064 to 10.64, and on the abscissa axis - from 0.5 to 5.0, i. e. $\sqrt{H_i / H_{i-1}} = \sqrt{9/0{,}09} = 10$ times.

A study of the developed grinding temperature mathematical model made it possible to establish its continuity with the existing solution of the one-dimensional differential equation of heat conduction under boundary conditions of the second kind on the surface. At the same time, the developed new mathematical model, in contrast to the mentioned one-dimensional solution, makes it possible to explicitly determine the penetration depth of any previously set grinding temperature.

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Дослідження спрощеної моделі температури шліфування

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Анотація. У роботі проведене дослідження спрощеної математичної моделі визначення температури шліфування. За отриманими рівняннями цієї моделі є відмінність результатів від відповідного більш точного розв'язання одновимірного диференціального рівняння теплопровідності за граничних умов другого роду. Досліджувана модель представлена системою з двох рівнянь, що описують температуру шліфування на етапах нагрівання і охолодження без використання примусового охолодження. Обсяг досліджуваної моделі відповідає сучасним технологічним операціям шліфування на верстатах із ЧПК для умов, коли числове значення числа Пекле перевищує 4. Це, у свою чергу, відповідає критерію Егера для так званого джерела тепла, яке швидко рухається, для якого параметр швидкості заготовки може бути еквівалентно за температурою замінений часом дії джерела тепла. Це дає можливість використовувати більш простий розв'язок одновимірного диференціального рівняння теплопровідності при граничних умовах другого роду (одновимірна аналітична модель) замість аналогічного двовимірного розв'язку з невеликим відхиленням результатів розрахунку температури шліфування. Встановлено, що запропонований спрощений математичний вираз для визначення температури шліфування відрізняється від більш точного одновимірного аналітичного розв'язку не більше ніж на 11 % і 15 % на етапах нагрівання та охолодження відповідно. Порівняння даних щодо зміни температури шліфування за звичайним і розробленим рівняннями показало, що ці рівняння близькі та мають дві точки збігу: на поверхні та на глибині (приблизно зниження температури втричі). Також встановлено, що характер співвідношення між масштабами зміни числа Пекле (0,09 та 9) та глибиною температури подрібнення (1 та 10) становить 100 (9/0,09) і 10 (10/1) відповідно. Крім того, розкрито ще один нетрадиційний механізм для обох порівняних рівнянь: більш висока температура на поверхні супроводжується нижчою температурою на глибині.

Ключові слова: температура шліфування, етап нагрівання, етап охолодження, безрозмірна температура, температурна модель.