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# NONSTATIONARY AND DISCONTINUOUS GRINDING TEMPERATURE DETERMINATION

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## ОПРЕДЕЛЕНИЕ ТЕМПЕРАТУРЫ НЕСТАЦИОНАРНОГО И ПРЕРЫВИСТОГО ШЛИФОВАНИЯ

*Purpose. Because in known techniques entry parameters characterizing not only grinding wheel geometry, but also grinding modes, it is necessary to work out the techniques with entry parameters which invariant to the modes of grinding.*
*Design/methodology/approach. The superposition method created a mathematical model for determination of discontinued grinding wheel temperature. As a result a possibility was to compare the model with the known one. It gave the condition to find time constant and evaluate transient time after which the both models will be identical to the temperature calculated. The benefits of this study are a new presentation of the grinding temperature consisting of a periodic part superposed on the rising temperature due to the average surface flux. The values of both parts are given and analyzed and then used to find grinding temperature by changing the discontinued grinding wheel geometry parameters: the number of cutting ledges and their fill factor on the discontinued wheel circuitous step. The more the parameters mentioned the less the discontinued grinding temperature will be. The study allows choosing the optimal geometrical parameters of the discontinued grinding wheel on the bases of conformities to law of influence of discontinued grinding wheel geometrical parameters on the grinding temperature. Corresponding recommendations on the choice of discontinued grinding wheel geometrical parameters are presented in some detail as thoroughly as possible.*
*Findings. The each optimal geometrical parameter intervals of discontinued grinding wheel that does not depend on the grinding modes are found.*
*Originality/value. The change intervals of the each optimal parameters of discontinued grinding wheel may be chosen depending on the minimum discontinued grinding temperature.*
*Keywords: discontinued grinding, temperature, geometrical parameters of discontinued grinding wheel.*

**Introduction** The variety of constructive forms of machine parts is determined by the form of their individual surfaces and combinations of these surfaces. When these surfaces are machined even at one technological operation step there are changes of geometric, thermo-physical and technological parameters in the machining. For example, when a flat surface of a workpiece is grinding in a multi-clamping device for each next workpiece there are changes in value of allowance for processing, hardness of the material, geometry of the contact zone and, in addition, there is a change in the cutting capacity of the grinding wheel as it is worn. Considering these changes in time for geometrical, technological and thermal parameters of the machining, we can conclude that there are no constant over time (that is stationary) machining processes [1]. On the other hand the thermo-physical process schemes for temperature evaluation are usually simple, have constant parameters and do not correspond to the actual time-dependent complex phenomena occurring during cutting and abrasive machining. For example, moving heat source thermal scheme on the basis of which the grinding temperature calculations are performed is a simplified diagram of processing that takes place in some short time stages for the flat and round grinding. However, even in this case there is a transition to establish the steady temperature field around the moving heat source. Duration in time of this transition, that is thermal saturation time, is measured from the beginning of the heat strip source movement to the end of the transition in the moving coordinate system.

The task of developing the thermal phenomena theory in grinding is relevant, for example, to discontinuous, composite, and highly porous grinding wheels, which differ from traditional thermal problems with a continuous heat flux by discrete (pulse) representation of the heat sources – grains of a wheel. Feature of these grinding processes is the uncertainty of its transition from transient (initial) state to steady (final) one, which is manifested in the grinding temperature changing at the heating stage. Taking into consideration the discrete nature of heat generation is important in the calculation of surface and near-surface instant temperature, as with increasing a distance from the discrete surface heat flux it is transformed into a smoother and continuous one.

**The purpose of research** is to establish the conditions for the transition from a no stationary thermal process state to a steady one for the moving and fixed coordinate system and on the basis of these conditions to develop a mathematical model to determine the temperature due to the periodic grinding heat flux on a surface of a workpiece. And for any heat flux frequency, that is, for both micro and macro discontinuous grinding.

**Presentation of the basic material** Thermo-physical scheme on the basis of which calculations of grinding temperature are made includes a moving strip source, the length of which is $2h$ and which moves with velocity $V$ (Figure 1).

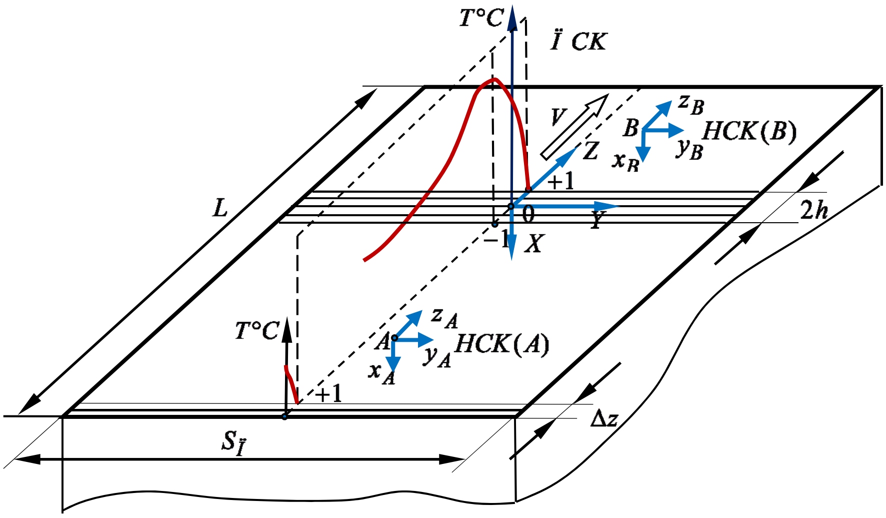


**Fig. 1. Thermophysical scheme of the thermal process in grinding**

Temperature field formation is usually viewed in two coordinate systems: the moving coordinate system (MCS), which is connected to the moving heat source, and the unmoving one (UCS), belonging to individual points of the machining surface. The published formulas for determining the temperature of the MCS had been obtained for stationary (time-independent) thermal field of the source. This stationary field is formed over time of transition $\tau_{t.p.}$, known as "the heat saturation time." It is necessary to distinguish between two moving heat sources: a practical source (close to the real one) and a theoretical one (existing in the mathematical sense). A description of a phased transition process of the temperature field formation for practical moving heat source might be done as follows (Fig. 2a).

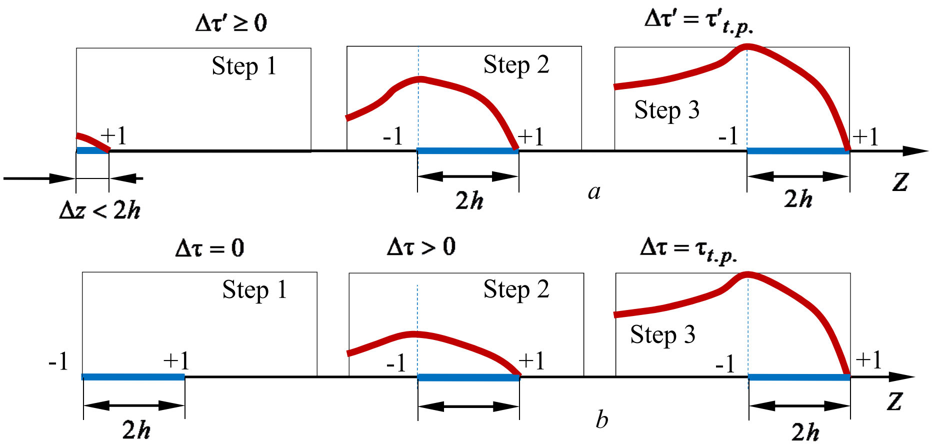


**Fig. 2. Steps of formation of the temperature field around the practical (*a*) and theoretical (*b*) moving heat sources**

1. The beginning of the transition process for the practical source is measured from the initial touch between a wheel and a workpiece (step 1 in Figure 2, a). Then the variable stripe length of contact with the current length $\Delta z = V\Delta\tau'$ is formed, where $0 \le \Delta\tau' \le \tau'_{t.p.}$ – is the current time on the interval of the transition, i.e, transient, period. The length $\Delta z$ of this strip during a non-stationary time interval is less, then $2h$ i.e. $\Delta z < 2h$ (step 1 in Figure 2, a).

2. After some time, the length of the strip reaches its steady state value $2h$ (step 2 in Figure 2, a).

3. Then temperature field in the MCS stops its changing as along the coordinates $X, Y, Z$ (see Figure 1), and in the time interval which is measured after the end of the interval of the transition process $0 \le \Delta\tau' \le \tau'_{t.p.}$ (step 3 in Figure 2, a).

A similar staged formation of the theoretical moving heat source the following.

1. A source with the length (width) $2h$ at the time $\Delta\tau = 0$ has touched the workpiece and simultaneously begun to moving with velocity $V$ in the axial direction $Z$ (step 1 in Figure 2, b).

2. After a while $\Delta\tau > 0$ an intermediate transient temperature field is forming around the moving source (step 2 in Figure 2, b).

3. When $\Delta\tau = \tau_{t.p.}$ the temperature field change stops. It will not be the change as to the coordinates $X, Y, Z$ in the MCS (see Figure 1) and the time also (step 3 in Figure 2, b).

Thus, at the moment of contact of a grinding wheel and a workpiece the first transient formation of the temperature field of a moving heat source begins in the MCS. After the first transition, during which there is a non-stationary mode (temperature field is non-stationary), the thermal saturation occurs, after which the moving heat source temperature field will be stationary (quasi-stationary), i.e. independent of time (see graph on the vertical plane in Figure 1). The term "stationary" (quasi-stationary) refers to the temperature field, which is formed in the MCS (this MCS goes together with a heat source). After the first transition process ends the presence of the built-in grinding wheel thermocouples can fix the maximum surface temperature of the grinding (the output of the thermocouples). It is taking place in the area of the rear edge of the source in the MCS. The steady temperature at any point in grinding with the coordinates $Z$ and $X$ is found by the well-known equation for the two-dimensional mathematical model of a quasi-stationary temperature field [2].

Farther, the transition process in the MCS for the theoretical moving heat source will be called “the time of the first transition” in contrast to “the time of the second transition” in the unmoving coordinate system (UCS). Note also that the achieved moving heat source steady-state thermal field corresponds only to the instantaneous state of the source and at any time can be broken. It is sufficient, for example only to change the velocity $V$ of the source, all other things being equal and achieved temperature stability $T(X_i, Y_i, Z_i, V)$ in the MCS is broken and a new transient formation of the steady temperature begins once again. This new transition process ends with the formation of new steady-state values of the temperature in the same points belonging to the MCS. For example, for the same $i$ - th point a new steady-state temperatures will be $T'(X_i, Y_i, Z_i, V')$ and $T(X_i, Y_i, Z_i, V) \neq T'(X_i, Y_i, Z_i, V')$ that is, when the velocity changes its value from $V$ to the $V'$ stationary temperature changes from $T$ to $T'$.

Thus, the published two-dimensional mathematical model of the temperature field describes the stationary thermal process, i.e. after the temperature field in the MCS has been stabilized around the moving heat source. Many researchers are unjustifiably use this model and do not compare the first transition time with a real grinding machine time separately for each machining workpiece including a multiprocessing of work pieces when they are placed in the join of the ends to each other, for example, on a table of the surface grinder. However, the temperature field during the time of a machine table longitudinal stroke "does not jump" from one workpiece to another because of their adiabatic walls. In each of the work pieces the first transition temperature change process takes place. If the length of the workpiece is negligible (less than 5 mm), the time of the first transition (the thermal saturation) is comparable to the time machine processing of individual workpiece.

In applied problems the grinding temperature is determined at different points in the NCS centered on the surface point which is under consideration (see point A or point B in Figure 1). Temperature field at these points appear after moving strip heat source has been formed and then in its motion it passes over the surface point which is under consideration. The stages of this process are as follows.

1. Initially this point is combined with an anterior edge of the heat source which is located at the coordinate $Z = +1$ (Figure 1).

2. After the heating time $\tau_{\text{H}} = \dfrac{2h}{V}$ over this point it will be the rear edge of the moving heat source ($Z = -1$).

As a result, the temperature at this point will be increased to a maximum level determined by the heating time. In connection with this temperature changing the second transition in the UCS, different from that described above in the MCS takes place in the UCS. The mechanism of the second transition consists in sequential increasing temperature of the point (e.g, point A in Figure 1) as well as all points lying below in the surface layer along the coordinate $x_A$ (see Figure 1). Here it is assumed that by the given moment of time a moving heat source has been formed and the grinding time exceeds the saturation that, i.e. the first transition is over. It should be noted that if the first transition is not over, then it would not be quasi-stationary thermal field around the moving heat source. Accordingly, there would not be the temperature distribution along the coordinate $x_A$ (see Figure 1). Therefore, before evaluating the temperature at point A and along the coordinate $x_A$ (see Figure 1), you must ensure that the first transition is over, i.e. machining time exceeds the current grinding heat saturation that $\tau_{t.p.}$ (it is indicated the saturation time for the theoretical heat source, as for the practical one the problem is still not only resolved, moreover, it is not even set).

The observed change in temperature at the point considered (e.g. point B in Figure 1), as well as at other points over the depth of the surface layer is a reaction or response function to an abrupt heat flux change at this point (the boundary condition of the second kind).

Described transients feature (for the first transient and the second one) is stabilization of the temperature level in the first transient (quasi-stationary temperature field), and absence of that in the second one: under the second kind boundary conditions surface temperature and that over the surface layer depth always increases in the interval of heating. In this case the second transition process contains a section with relatively rapid changes in temperature, which can be called quasi transition process, during which the temperature is relatively quickly reaches a high level that is close to the maximum level.

In relation to discontinued grinding the temperature is composed of two components: an aperiodic component and a periodic one. The amplitude of the periodic component is also subjected to the transient, during which it will be stabilized relatively quickly. It is found that the results of calculations of the maximum grinding temperature on the equations of two - and a one-dimensional mathematical model (for stationary and non-stationary processes, respectively) do not differ by more than 10% [2], provided that the first transition is over. Therefore, it is advisable for process design and technological diagnostics of the grinding process using a one-dimensional model thermo-physical scheme with a linear heat flux. According to this scheme, the thermal field is created by the heat flux movement over the coordinate $x$ of the heat flux with parallel vectors of its density.

The temperature in the grinding zone can be adjusted, if the grinding is produced with a certain time grinding breaks over the next time interval $0 \le \tau \le \tau_H$ . This allows you to change the character of the temperature field and the maximum temperature in the contact zone when the discontinued periodic heating of the workpiece surface is alternated with its periodic absence. This process can be done with special grinding wheels having on the working surface a series of alternating ledges and cavities with certain extent, which pairs form cycles of heating (ledges) and cooling (cavities). For example, if the length of the ledge $l_1$ and cavity $l_2$ , the amount of heating time in the contact zone $T_1 = \frac{l_1}{V_{wh}}$ ($V_{wh}$ – linear velocity of the wheel rotation) each time alternating with the corresponding cooling time interval $T - T_1 = \frac{l_2}{V_{wh}}$ , where $T$ – micro cycle timing, *s*.

During operation of the ledge (heating) there is a heat flux $q(\tau) = q_{\max}$ for time $T_1$ in the contact zone and there is no one, that is absence of cutting or cooling, without operation of the ledge (cavity) for time $T - T_1$ Thus, the heat flux acting on the work surface can be represented by the following step function [3]

$$q(\tau) = q_{\max}\text{ , at } nT < \tau < nT + T_1, \quad n = 0,1,...$$

$$q(\tau) = 0\text{ , at } nT + T_1 < \tau < (n+1)T, \quad n = 0,1,...$$

In other words the heat flux $q(\tau)$ is "on" for time $T_1$ and "off" for time $T - T_1$ , and so on, with period $T$ .

A continuous sequence of the "heating-cooling" cycles is located on the site of heating, the duration of which both for continuous and discontinuous circle is determined by time $\tau_H = \frac{2h}{V}$ . To optimize the heat generation it is necessary to obtain the discontinued grinding temperature dependence on the wheel geometric parameters, which include the number of ledges $N$ on the wheel and fill factor $S$ at the cycle step. Also note that when the discontinued grinding wheel cavity is situated in the contact zone then a heat flow absence is accompanied by absence of material removal, which results in a corresponding additional load on the next ledge of the wheel and, as a consequence, an additional heat flux additive (i.e. increasing) at this ledge of the wheel. In accordance with the proposed method it is formulated condition of constant grinding intensity (of cutting work and power), which should be available for all constructions of the discontinued wheels comparing each with other. This condition of constancy must be accompanied by constant cutting power in the grinding. The constancy of the cutting power at fixed regime parameters and the diameter of the wheel is accompanied by constant heat flux. So the above condition of the grinding intensity constancy is provided by the relative constancy of the average heat flux density $q_{ave}$ .

The following approach to the determination of the temperature field in the discontinued periodic action of heat flow is proposing in the paper. It is known that in the absence of forced cooling the machining surface the temperature fields from the action shifted over time heat sources is under the principle of superposition: the temperature on different locations of the field can be summarized by adding the temperature of the same spatial coordinates. The essence of the principle of superposition as applied to the discontinued grinding is as fellows. Temperature field from a single rectangular pulse of heat flow, operating on a time interval $0 \le \tau \le T_1$ can be replaced by the sum of the temperature fields of action of the two time-continuous heat sources. The first heat source is a positive one ($+q_{\max}$ ). It acts continuously on a time interval $0 \le \tau \le \infty$ . Second heat source (matched with the first one) is a negative source ($-q_{\max}$ ). It operates continuously at a time interval $T_1 \le \tau \le \infty$ . This technique to represent a single pulse of the heat flux is known with respect to a single time interval of the heat flow in the ordinary grinding by continued grinding wheel. [2] The duration of this interval is characterized by macro cycle of grinding (Fig. 1). Applied to a discontinued grinding wheel such way to represent a single pulse of heat flow is preserved, but instead of using the heating time macro cycle it is used the heating micro cycle.

Applying the principle of superposition for any number of micro-cycles of heating and cooling, we obtain the following recursive formula for the determination of the discontinued grinding temperature in the heating interval

$$T = \frac{2q}{\lambda}\left(\sum_{i=1}^{n}\sqrt{a\left[\tau-(i-1)T\right]}\cdot ierfc\frac{x}{2\sqrt{a\left[\tau-(i-1)T\right]}} - \sqrt{a\left[\tau-(i-1)T-T_1\right]}\cdot ierfc\frac{x}{2\sqrt{a\left[\tau-(i-1)T-T_1\right]}}\right). \quad (1)$$

where $\lambda$ и $a$ – thermal conductivity (W / (m ·° C)) and the thermal diffusivity (m$^2$ / s) of the processed material.

For plotting the grinding temperature on the grinding time (Fig. 3) from (1) in the medium MathCAD the following input data are accepted: $D$ = 390 mm (out of a possible range of 300 ... 400 mm), $l_1$ = 20 mm, $l_2$ = 15 mm, $V_{кр}$ = 35 m / s, $V$ = 2 m / min, $t$ = 0,028 mm, $q_{max}$ = 40 10$^6$ W/m$^2$, $\lambda$ = 42 W / (m • ° C) = 8 10$^6$ m$^2$ / $s$.

Under these conditions $l_1$ + $l_2$ = 35 mm, the number of ledges on a discontinued wheel $N$ = 35, the time of one complete revolution of the wheel 35 ms, the acting time of a unmoving plane heat source 100 ms, the number of turns per a while $\tau_H$ is equal to 2.9. Thus, one discontinued grinding micro cycle duration of $\tau_H$ = 100 ms has 100 micro cycles $T$ = 1 ms, a time interval of one revolution of a wheel is equal to 35 micro cycles of grinding.

The time constant of the transition process can be found from the following equation

$$\frac{2q_{max}}{\lambda}\sqrt{\frac{aT_1}{\pi}} = \frac{2q_{ave}}{\lambda}\sqrt{\frac{a\tau_t}{\pi}}.$$

Taking into account the relationship between the parameters $q_{max}$ and $q_{ave}$ we can obtain

$$\tau_t = \frac{T}{S} = TQ, \quad (2)$$

where $Q$ - is the duty factor of the heat flux square wave.

For this case ( $S$ = 0, 5714), the time constant of the transient is 1,75 ms.

Time of exponential transition $T_t$ will be

$$T_t = 3\tau_t = 3\frac{T}{S} = 3TQ < \tau_H \quad (3)$$

For this case the transient time 1,75 · 3 = 5.25 ms, which corresponds to the selected time interval in Figure 2.

In the program MatLAB it is calculated the grinding temperature by the formula (1) in the whole interval of heating $0 \le \tau \le \tau_H$ in grinding (Fig. 3).

There are following designations on Fig.2: 1 – the rising temperature due to the maximum surface heat flux $q_{max}$, 2 - discontinued grinding total temperature 3 - the rising temperature due to the average surface heat flux $q(\tau) = q_{ave} = \frac{q_{max}T_1}{T}$ at $S$ =0,5714, 4 – a fragment of periodic steady temperature component.

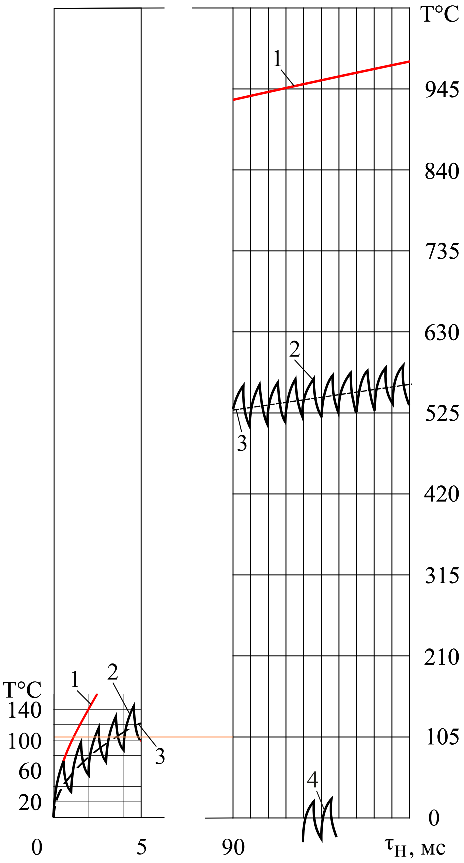

**Рис. 2. Discontinued grinding temperature ( $N$ = 35) over the transient time interval (*a*) and the steady one (*b*)**

It can be seen that the temperature of the discontinued grinding (curve 2 in Figure 3) can be ultimately represented as the sum of two components: the rising temperature 3 and periodic steady temperature 4.

The resulting mathematical model (1) to determine the temperature of the discontinued grinding can be used to study the temperature field at any frequency of periodic heat flux, including the frequency for the heat sources - grains of the grinding wheel. In order to solve this task it is necessary to have an appropriate geometrical model of a grinding wheel, and a corresponding thermo-physical scheme for the thermal process. In this case, even an ordinary continued grinding wheel can be represented by a model of micro-discontinued grinding wheel which has a ledge - grinding active grain, and a cavity - air hollow, which is characteristic, for example, for high-porosity grinding wheel. Thus the equation (1) obtained above can be used to determine grinding temperature both for discontinued and continued grinding wheel.

**Conclusions**

1. A necessary condition for the adequacy of the two-dimensional steady-state solution of the differential equation of heat conduction is the end of the transition process, the temperature change in the moving coordinate system; the duration of this transition is the time for the heat saturation.

2. A sufficient condition for the application of two-dimensional steady and unsteady one-dimensional solution (after the necessary condition) for a description of continuous and pulsed rising temperature is the end of the second transition temperature changes in a fixed coordinate system in which, for example, in relation to discontinued grinding, the amplitude of the temperature stabilizes pulses in this system.

3. The equation (1) is obtained to determine the temperature due to the pulse grinding heat flux at any frequency of its ”on” and “off”. Equations (2) and (3) are set to determine the time constant and the total time of the transient temperature changes both in the discontinued and continued grinding.

***Анотація.*** *Виконано аналіз перехідних процесів зміни температури шліфування в рухомої ї нерухомої системах координат відповідно для дво- и одновимірної математичної моделі температурного поля. Розроблена і досліджена математична модель для визначення температури переривчастого шліфування з урахуванням геометричних параметрів переривчастих шліфувальних кругів. Встановлено, що температура переривчастого шліфування містить дві складові: що безперервно зростає і періодичну імпульсну. Досліджений перехідний процес зміни температури, встановлена залежність для визначення часу перехідного процесу.*

Ключові слова: *переривчасте шліфування, температура, геометричні параметри переривчастих шліфувальних кругів .*

***Аннотация.*** *Выполнен анализ переходных процессов изменения температуры шлифования в подвижной и неподвижной системе координат соответственно для дву- и одномерной математической модели температурного поля. Разработана и исследована математическая модель для определения температуры прерывистого шлифования с учетом геометрических параметров прерывистых шлифовальных кругов. Установлено, что температура прерывистого шлифования содержит две составляющие: непрерывно возрастающую и импульсную. Исследован переходный процесс изменения температуры, установлена зависимость для определения времени переходного процесса.*

Ключевые слова: *прерывистое шлифование, температура, геометрические параметры прерывистых шлифовальных кругов.*

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