ANALYTICAL DETERMINATION OF CUTTING TEMPERATURE IN GRINDING AND CONDITIONS OF HER DOWN

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Abstract: The paper presents a simplified calculation according to the definition of cutting temperature during grinding, with which you can set the final values of the depth of penetration of heat into the surface layer of the workpiece. This allows a new approach of determining the optimal grinding conditions, because, in the known dependences, the character of spread of temperature in the depth of a surface of detail’s layer obeys an exponential law, which excludes the possibility of establishing a final (true) values of the depth of heat penetration into the surface layer of the workpiece and limit the uniqueness of the choice of optimum modes of grinding and range of characteristics.

Keywords: grinding process, the cutting temperature, heat flux, the skin depth, power consumption of the processing, intermittent grinding.

1. INTRODUCTION
Grinding process provides high levels of accuracy and roughness of the processed surfaces, but the processing of parts of hardened steels and other hard materials may lead to the formation of burns and microcracks. This is due to the increased power and thermal strength of the grinding process because of the friction of a circle binder with material being processed and wear of the cutting grains [1]. Currently, extensive experience of effective implementation of the grinding process prevents the formation of the temperature defects on the treated surfaces. This uses the discontinuous circles [2], effective technological environments, optimizing cutting conditions according to the temperature criterion and so on, what allowed fundamentally solve the problem of defect-free processing of machine parts, in particular, a high-precision parts of aviation purposes [3]. At the same time, to manage the process of grinding and to improve the quality and efficiency of processing it is important to know the physical laws of change of temperature of cutting during grinding and to know the conditions of temperature reduction. This requires analytical determination of cutting temperature in grinding and conducting its analysis for the further development of the theory of Thermal Physics of the grinding.

2. ANALYTICAL RESEARCH
Traditionally, the calculations of temperature of cutting during the grinding are made by using the heat equations [2]:

$$\frac{\partial \theta}{\partial \tau} = a^2 \cdot \left( \frac{\partial^2 \theta}{\partial x^2} + \frac{\partial^2 \theta}{\partial y^2} + \frac{\partial^2 \theta}{\partial z^2} \right),$$

where \(a^2 = \lambda / c \cdot \rho\) - a coefficient of thermal conductivity of the material being processed, \(m^2 / s\); \(c\) - the specific heat of the material being processed, \(J / (kg \cdot K)\); \(\lambda\) - the thermal
Conductivity of the material being processed, W / m · K; \( \rho \) - the density of the processed material, kg / m\(^3\); \( \tau \) - the processing time, sec; \( x, y, z \) - a coordinates.

Fig. 1. Diagram of calculation of cutting temperature at flat grinding:
1 - circle; 2 - piece; 3 - adiabatic rod

The solution of this equation usually presents a considerable difficulty. Therefore, in the work of Professor A. Yakimova [2] the solution of the equation (1) was obtained on the base of the use of simplified design scheme of the grinding process (fig. 1) in which the grinding wheel moves along the treated (flat) surface, and the workpiece is presented as a package of thin elementary adiabatic rods. In this case, the produced during grinding process heat adiabatically extends only along the rod, i.e. in the direction of the coordinate axis \( x \). It is assumed that the walls of rod are insulated, and the heat exchange does not occur between them. Then the analysis of thermal processes can be carried out on the base of a simplified solution of the heat equation (for transient with time thermal process) in a one-dimensional coordinate system:

\[
\frac{\partial \theta(x, \tau)}{\partial \tau} = a^2 \frac{\partial^2 \theta(x, \tau)}{\partial x^2} .
\] (2)

To calculate the grinding cutting temperature, the following initial and boundary conditions are taken:

\[
\theta(x, \tau)_{|\tau=0} = \theta_0 ; \quad \theta(x, \tau)_{|x=0} = \theta_u ; \quad \frac{\partial \theta(x, \tau)}{\partial x} |_{x=0} = 0 ,
\] (3)

where \( \theta_0 \) - the initial temperature of the detail is equal to the temperature of the environment; \( \theta_u \) - the temperature of the contact zone; \( \tau \) - the duration of the action of the heat source on the end of the selected elementary rod.

As a result, the temperature distribution with depth of the processed sample (elemental rod) is determined inside the grinding zone with check of a time exposure \( \tau = 2h / V_{det} \) of the heat source on the end of the selected elementary rod and with the check of the heat flow density \( q \):
\[
\theta_y = \frac{q}{2} \sqrt{\frac{2\pi \cdot h}{\lambda \cdot c \cdot \rho \cdot V_{\text{det}}}} \cdot \left[ 1 - \text{erf} \left( \frac{x \cdot \sqrt{V_{\text{det}}}}{2 \cdot \sqrt{\alpha^2 \cdot h}} \right) \right],
\]

where \(2h, V_{\text{det}}\) - the width and speed of the heat source.

The maximum temperature is reached at the end of the selected elementary rod, i.e. at the contact of the rod with a grinding wheel. With increasing coordinate \(x\), the temperature \(\theta_y\) continuously decreases without reaching a zero value. The reducing of temperature in the grinding zone is possible by reducing the heat flux density \(q\) and the time exposure \(\tau\) of the heat source.

A similar solution with the boundary \(\frac{\partial \theta}{\partial x} \bigg|_{x=0} = -\frac{1}{\lambda} \cdot q\) and initial conditions \(\theta|_{\tau=0} = 0\) was obtained in [4]:

\[
\theta(z) = 2 \cdot a \cdot \sqrt{\tau} \cdot \frac{q}{\lambda} \left[ \frac{1}{\sqrt{\pi}} \cdot e^{-z^2} - z \cdot (1 - \text{erf} z) \right];
\]

\[
q(z) = q \cdot (1 - \text{erf} z),
\]

where \(z = \frac{x}{2 \cdot a \cdot \sqrt{\tau}}\); \(x\) - coordinate, m; \(\tau\) - a time, sec.

Temperature \(\theta(z)\) and heat flow density \(q(z)\) with the depth of the surface’s layer of the processed material asymptotically decreases to zero (fig. 2). In this case, heat penetration depth into the surface layer of the material is infinite, whereas in the practice it takes a finite value. This is a significant drawback of the theoretical solutions, because it is impossible to unambiguously determine the true value of the thickness of the disturbed (the defective, in terms of thermal effects) layer of the processed material. Therefore, in the calculations, the depth of heat penetration into the surface layer of the processed material is determined at the predetermined specific temperature, for example, 20 °C. However, this is not practical grinding conditions.

To solve this problem, in [5] proposed a simplified approach of the definition of grinding temperature, based on the setting of the law of the density distribution of the heat flow in the depth of the surface layer of the processed material. It was found that in the case \(q(x) = q \cdot \left(1 - \frac{x}{\Delta x}\right)\) and the boundary condition \(\theta(x = \Delta x) = 0\) the solution takes the form

\[
\theta(z) = 1.225 \cdot a \cdot \sqrt{\tau} \cdot \frac{q}{\lambda} \cdot (1 - 0.816 \cdot z)^2;
\]

\[
q(z) = q \cdot (1 - 0.816 \cdot z),
\]

where \(\Delta x\) - the heat penetration depth into the surface layer of material, m.
Fig. 2. The graph of the function $\theta(z)$ (a) and $q(z)$ (b), described by the relationship:

1 - (5) and (6); 2 - (7) and (8); 3 - (9) for the condition $a \cdot \sqrt{\frac{A\tau}{q}} \cdot q / \lambda = 1$.

For the case $q(x) = q$ it was obtained:

$$\theta(z) = 1,414 \cdot a \cdot \sqrt{\frac{q}{\lambda}} \cdot (1 - 1,414 \cdot z).$$

As it was obtained, the maximum grinding temperatures obtained using the relations (5) and (7) and (9) are different within 15% (Fig. 2). The depth of heat penetration into the surface layer of the processed material, according to the obtained solutions (7) and (9), is assumed as a finite value. This results lead in line the practice and theory of Thermal Physics of grinding. Therefore, with sufficient accuracy for practical purposes, you can make calculations of maximum grinding temperature and heat penetration depth into the surface layer of the material on the basis of the proposed simplified solutions. This opens up new opportunities to identify ways of intensification of the grinding process, taking into account restrictions on the temperature factor. Thus, depending on the basis of (7), the analytical description of the temperature of grinding with the variation of number of interrupts $n$ of the grinding process was done [6]:

$$\theta_0 = \sigma \cdot \sqrt{\frac{2 \cdot \Pi^2 \cdot n}{c \cdot \rho \cdot \lambda \cdot m^2} \left( \frac{1}{\tau_1} - \frac{2 \cdot \alpha^2}{c \cdot \rho \cdot \lambda \cdot \tau_1^2} \right)};$$

$$\theta_{max} = \sigma \cdot \sqrt{\frac{2 \cdot \Pi^2 \cdot n \cdot \tau_1 - (n - 1) \cdot \frac{2 \cdot \alpha^2}{c \cdot \rho \cdot \lambda \cdot \tau_2^2}}{c \cdot \rho \cdot \lambda \cdot m^2 \cdot \tau_1^2}},$$

where $\sigma$ - conditional cutting voltage (power consumption of the processing), N / m$^2$; $\theta_0$, $\theta_{max}$ - temperatures after $n$-th heat pulse and the cooling of the workpiece, K; $\alpha$ - heat transfer coefficient, W / (m$^2$ · K); $\Pi$ - the value of the taken allowance, m; $m$ - the number of partitions of the allowance; $\tau_1$ - the duration of the heat pulse, sec; $\tau_2$ - cooling time of the workpiece, s.

The calculations revealed that a decrease in the time $\tau_1$ from 0.356 to 0.089 s, a total processing time is decreased $\tau = m \cdot \tau_1 + (m-1) \cdot \tau_2$ from 1.43 s up to 0.535 s for a given maximum temperature grinding $\theta_{max} = 1000^\circ C$ (fig. 3). Initial data: $\sigma = 10^5$ N / mm$^2$; $\rho = 14,5 \cdot 10^3$ kg/m$^3$; $c = 40$ cal/(kg · hail); $\lambda = 14$ cal/(m·s·hail); $\alpha = 10^4$ cal/(m$^2$ · s · hail); $\Pi = 0.1$.
мм; $m = 4$; $\tau_2 = \sqrt{\frac{\tau_1 \cdot (4 - 11.236 \cdot \tau_1)}{75}}$.

Fig. 3 also shows that under the condition $\tau_1 = 0.089$ s the complete cooling of the workpiece occurs in the moment of time of interruption of the milling process, and at $\tau_1 > 0.089$ s - incomplete cooling. Therefore, the achievement of the greatest effect of processing is possible in the case of $\tau_1 = 0.089$ s.

Three basic conditions of temperature reduction $\theta_0$ follow from relation (10). The first condition is to reduce the energy intensity of treatment $\sigma$, and the second - to increase $m$, and the third - to ensure equality of terms under square root of (10). Implementation of the third case involves the stabilization with time (with increase $n$) of the maximum temperature $\theta_{\text{max}}$ (Fig. 3a) through the use of intermittent grinding or the reciprocating motion of the circle and of the workpiece.

Fig. 3. The character of the changes of temperature grinding $\theta$ with processing time $\tau$:

- a - $\tau_1 = 0.089$ s
- b - $\tau_1 = 0.178$ s
- c - $\tau_1 = 0.267$ s
- d - $\tau_1 = 0.356$ s
In [7], similar to the above listed solutions, approximate formulas were obtained for calculations of the maximum grinding temperature $\theta_{\text{max}}$, depth $l_2$ and speed $V_\theta$ of propagation of heat deeply into the surface layer:

$$\theta = q \cdot \sqrt{\frac{2 \cdot \tau}{\lambda \cdot c \cdot \rho}}; \quad l_2 = \sqrt{\frac{2 \cdot \lambda \cdot \tau}{c \cdot \rho}}; \quad V_\theta = \frac{dl_2}{d\tau} = \sqrt{\frac{\lambda}{2 \cdot c \cdot \rho \cdot \tau}}.$$

On the basis of these dependences, the basic conditions for reducing the maximum temperature of cutting $\theta_{\text{max}}$ during grinding are the reducing of the heat flux density $q$ and the time of its action on a fixed point of the treated surface, and reducing the depth of penetration of heat $l_2$ - the reducing of time $\tau$. This is achieved by reducing the power strength of the grinding process (by increasing the cutting capacity of the wheel (circle) and by reducing the friction in the grinding zone) and applying intermittent grinding. The reducing of time $\tau$ is possible due to the increasing speed of the heat source $V_{\text{det}}$ (Fig. 1), performing multipass grinding. Application of deep grinding $V_{\text{det}}$, carried out at low speed, requires the increased time $\tau$. Therefore, to achieve reduction of grinding cutting temperature in this case may be by a decreasing of the heat flux due to the use of highly abrasive wheels providing low friction intensity in the cutting zone.

REFERENCES


