

## Research on operation mode of abrasive grain during grinding

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**Abstract.** The processing of materials by cutting with an abrasive tool is carried out by means of thousands of grains bonded together as a single whole. The quality of the abrasive tool is defined by cutting properties of abrasive grains and depends on features of spreading the temperature field in time and in the abrasive grain volume. Grains are exposed to heating and cooling during work. It leads to undesired effects such as a decrease of durability of grain retention in the binder, hardness, intensification of diffusion and oxidation processes between the binder and the grain, the occurrence of considerable temperature stresses in the grain itself. The obtained equation which allows calculation of temperature field of grain for one rotation of grinding wheel shows that the temperature of the wheel depends on grinding modes and thermophysical properties of abrasive material. Thus, as the time of contact of grain with processed material increases, the temperature in the cutting area rises. As thermophysical properties increase, the temperature in cutting area decreases. Thermal working conditions are determined to be different from each other depending on contact time of the grain and the material. For example, in case of creep-feed grinding, the peak value of temperature is higher than during multistep grinding; the depth of expansion is greater. While the speed of the thermal process in creep-feed grinding is 2-3 times lower than in multistep grinding, the gradient reduces 3-4 times. The analysis of machining methods shows that creep-feed grinding ensures greater depth of grain heating, a smaller heating rate and a reduced velocity gradient. It causes a decrease of probable allotropic modifications and prevents from occurring of heat strokes - cracking of grains due to high temperature falls. Consequently, it is necessary to employ creep-feed grinding to increase the efficiency of abrasive tool employing. Three operation modes of grinding wheel including blunting, full self-sharpening, emergency wear and tear are determined as the result of the research on evaluation of cutting ability of grinding wheels. Recommendations for working capacity of grinding wheels in each operation mode and with a transition from one mode to another are given. As a result of the research, different dependencies were determined. They include dependencies, governing the extent of influence of granularity, difference in height and concentration of grains, geometry parameters of the detail to be machined and the grinding wheel on machining modes and the thickness of the layer cutoff by one grain. They have an influence on the grinding process.



## 1. Introduction

The final stage of detail production includes operations of abrasive treatment, which allow us to get high accuracy and quality of treated surfaces. The main requirements, applicable to abrasive treating especially to grinding, are reduced to increasing of output capacity and quality of the obtained treated surface. During grinding, these requirements are met by either improving the quality of the abrasive tool or rational control of the detail treatment process [1 – 30].

## 2. Materials and methods

The machining of materials is carried by thousands of tiny grains of different geometry bonded together as a single whole by means of binding material. Between separate cutting edges of abrasive grains, there is a place for swarf entry. The greater the cutting speed is and the less the cross-section of cutoff layer is, the more productive the process will be. When the speed is high, the resistance of cutting edges is low. However, due to their great number and new cutting edges entering the process periodically, actual wear and tear of the tool remain small.

The quality of the cutting tool is comprehensively determined by the cutting properties of the abrasive grains, the properties of the binding material and the structure of the abrasive tool. The quality of the material of abrasive grains is the most important one among three technical characteristics of the abrasive tool. It largely depends on the specific features of the temperature field transfer over time and the volume of abrasive grain. During the operation process, grains are exposed to heating and cooling over and over again. It causes undesired effects, such as decreasing the strength of keeping grains in binding, decreasing the hardness, intensification of diffusive and oxidative processes between binding and the grain, occurrence of considerable temperature stresses in the grain itself. Residual temperature stresses considerably influence grain properties and the nature of its fracture behavior. Surface layers of the grain during its contact with a machined detail are heated to considerable temperatures and tend to expand. Lower layers hinder that; that is why they become compressed. When the grain leaves the cutting area, surface layers will be compressed; but due to resistance of lower layers, they will face tensile stress. Therefore, tensile strength can serve as a criterion of the destruction of the grain depending on the temperature stresses. For example, for diamond grains of grade AC6 with a granularity of 200/160 (Russian State Standard (GOST)), stresses up to 210 MPa can occur, which is comparable to a tensile strength of 250 MPa.

One of the factors determining physical and mechanical properties of grain and cutting characteristics of the abrasive tool in case of destruction is their thermal resistance. Under conditions of multiple cyclic thermal effects, it depends on the value of critical temperature difference  $T_{start} - T_{cool} = \Delta T$ , the absolute values of each of the temperatures and their gradients.

Experimental determination of the temperature field of the grain is complicated by operating conditions and small sizes. Therefore, mathematical modeling of the grain temperature field becomes relevant. Analytical research of the field allow us to find the most important regularities of thermal phenomena in grains and estimate the extent of their influence on the grinding process.

During studying the heat transfer process in the system grain-machined surface, grains are sources of thermogenesis. The power of heat impulses depends on the geometric form of grains, the value of their cutting in the machined surface and cutting speed. The thermal process in the grinding area is determined by the combination of a huge amount of high temperature centers - heat impulses. Thermophysical parameters remain constant in the temperature interval under consideration. Let us assume that two thirds of the abrasive grain are submersed in the binding material and the grain represents a semi-bounded body. The cutting surface of the grain is exposed to heat impulse: heating during time  $t_0$  and cooling during time  $t - t_0$ . The heat exchange of the grain with the environment occurs according to the Newton-Richmann law.

Taking into account accepted admissions, let us find temperature distribution in the system consisting of two bodies with heat source placed in the interface plane. As the main direction of heat

transfer, let us accept the direction which is perpendicular to the surface in which the velocity vector is placed. The solution of the differential equation system:

$$\begin{cases} \frac{\partial T_1(x,t)}{\partial t} = a_1 \frac{\partial^2 T_1(x,t)}{\partial x^2}, (t > 0, -\infty < x < 0); \\ \frac{\partial T_2(x,t)}{\partial t} = a_2 \frac{\partial^2 T_2(x,t)}{\partial x^2}, (t > 0, 0 < x < \infty). \end{cases} \quad (1)$$

With initial and final conditions:

$$\begin{aligned} T_1(x,0) = T_2(x,0) = 0, \\ \left. \begin{aligned} T_1(0,t) = T_2(0,t), \\ \lambda_1 \frac{\partial T_1(0,t)}{\partial x} + \lambda_2 \frac{\partial T_2(0,t)}{\partial x} = q, \end{aligned} \right\} (0 < t < t_0), \\ -\lambda_2 \frac{\partial T_2(0,t)}{\partial x} + \alpha_2 T_2(0,t) = 0, (t_0 < t < t_1), \end{aligned} \quad (2)$$

where  $T_1$  – the temperature of the detail;  $T_2$  – the temperature of the grain;  $\lambda_1, \lambda_2$  – thermal conductivity ratios of the detail and the grain, respectively;  $a_1, a_2$  – temperature conductivity coefficients;  $\alpha_2$  – heat transfer coefficient.

For grain, it can be represented in the following form:

$$\begin{aligned} T_2(x,t) = \frac{1}{1+k} \cdot \frac{q}{\sqrt{\pi \cdot c_2 \lambda_2 \rho_2}} \int_0^{t_0} \frac{1}{\sqrt{t-t'}} \exp\left(-\frac{x^2}{4a_2(t-t')}\right) dt - \\ - \frac{\alpha}{k} \cdot \frac{1}{1+k} \cdot \frac{q}{\sqrt{\pi \cdot c_2 \lambda_2 \rho_2}} \int_{t_0}^{t_{0x}} \frac{1}{\sqrt{t'-t_{0x}}} \exp\left(-\frac{(x+x'')^2}{4a_2 t'_{0x}} - \frac{\alpha}{\lambda_2} x''\right) dx'' dt'_{0x}, \end{aligned} \quad (3)$$

where  $q$  – heat flow density;  $c_2$  – heat capacity;  $\rho_2$  – density;  $k = \sqrt{\lambda_1 c_1 \rho_1 / \lambda_2 c_2 \rho_2}$  – coefficient characterizing the activity of interaction of the machined material and the grain;  $t_{0x}$  – time of cooling;  $\alpha$  – heat transfer coefficient.

After the transformation of equation (3), let us obtain a dependence which allow us to calculate the temperature on the surface and by grain depth during the heating (cutting) and cooling stages:

$$\begin{aligned} T_2(x,t) = \frac{1}{1+k} \cdot \frac{2q}{\sqrt{c_2 \lambda_2 \rho_2}} \left[ \sqrt{t} \cdot \text{ierfc}\left(\frac{x}{2\sqrt{a_2 t}}\right) - \sqrt{t-t_0} \text{ierfc}\left(\frac{x}{2\sqrt{a_2(t-t_0)}}\right) - \right. \\ \left. - \frac{\alpha a_2}{2\lambda_2} \int_{t_0}^{t_{0x}} \exp\left(\frac{\alpha^2}{\lambda_2^2} a_2 t'_{0x} + \frac{\alpha}{\lambda_2} x\right) \text{ierfc}\left(\frac{x}{2\sqrt{a_2 t'_{0x}}} + \frac{\alpha}{\lambda_2} \sqrt{a_2 t'_{0x}}\right) dt'_{0x} \right]. \end{aligned} \quad (4)$$

The first term of equation (4) describes the process of heat transfer from a source of power  $q$ , which acts for time  $t$ . As for the integral, it characterizes the heat exchange with the environment after the heat source ceases to function.

The depth of penetration of heat impulse can be determined by dependence:

$$x = 3,6\sqrt{a_2 t}. \quad (5)$$

Equation (4) allows us to calculate the temperature field of the grain for one rotation of the grinding wheel and shows that grain temperature depends on grinding modes and thermophysical properties of abrasive material. Thus, by increasing the time of contact of the grain with machined material, the temperature in the cutting area increases. By increasing thermophysical parameters of the abrasive, the temperature in the cutting zone decreases.

To estimate the temperature in the cutting area according to time of heating or cooling, let us carry out respective calculations for both machining methods - multistep and creep-feed grinding. Let us consider thermal phenomena which occur during machining grooves in hard alloy HS123 (T15K6 - Russian State Standard (GOST)) by means of diamond grinding wheels with a diameter of 150 mm (MO4-120/100-100 % Russian State Standard (GOST)). Their thermophysical parameters are: index 1 belongs to the machined material (T15K6); index 2 belongs to abrasive grain (diamond)  $a_1 = 10^{-5} \text{ m}^2/\text{s}$ ,  $\lambda_1 = 27.3 \text{ J}/(\text{m} \cdot \text{s} \cdot \text{K})$ ,  $\rho_1 c_1 = 1.1 \text{ J}/(\text{m}^3 \cdot \text{K})$ ,  $a_2 = 8.3 \cdot 10^{-5} \text{ m}^2/\text{s}$ ,  $\lambda_2 = 146 \text{ J}/(\text{m} \cdot \text{s} \cdot \text{K})$ ,  $\rho_2 c_2 = 1.54 \text{ J}/(\text{m}^3 \cdot \text{K})$  during the following modes: multistep grinding -  $V_{cr} = 20 \text{ m/s}$ ,  $S_m = 1.5 \text{ m/min}$ ,  $t_m = 2 \cdot 10^{-5} \text{ s}$ ; creep-feed grinding -  $V_{cr} = 20 \text{ m/s}$ ,  $S_c = 0.05 \text{ m/min}$ ,  $t_c = 1 \cdot 10^{-3} \text{ s}$ .

The time of action of heat source

$$t_m = \frac{l_m}{V_{cr}} = \frac{\sqrt{t_m \cdot D}}{V_{cr}} = 8,1 \cdot 10^{-6} \text{ s}; \quad t_c = \frac{l_c}{V_{cr}} = \frac{\sqrt{t_c \cdot D}}{V_{cr}} = 6,4 \cdot 10^{-4} \text{ s}.$$

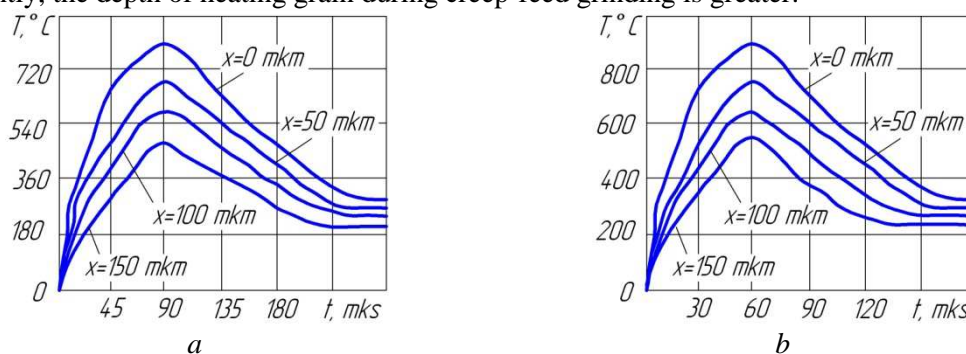
$$\text{The time of the whole cycle } t = \frac{\pi \cdot D}{V_{cr}} = 2,35 \cdot 10^{-2} \text{ s}.$$

Heat flow density is calculated through the cutting area maximum temperature which is determined experimentally for given machining modes:  $910^\circ\text{C}$  - for multistep grinding and  $960^\circ\text{C}$  - for creep-feed grinding. If  $t = t_0$ , let us obtain the following from equation (4):

$$q = \frac{T_{2\max}(x, t) \cdot \sqrt{c_2 \lambda_2 \rho_2} \cdot (1 + k)}{2\sqrt{t} \operatorname{erfc}\left(\frac{x}{2\sqrt{a_2 t}}\right)}. \quad (6)$$

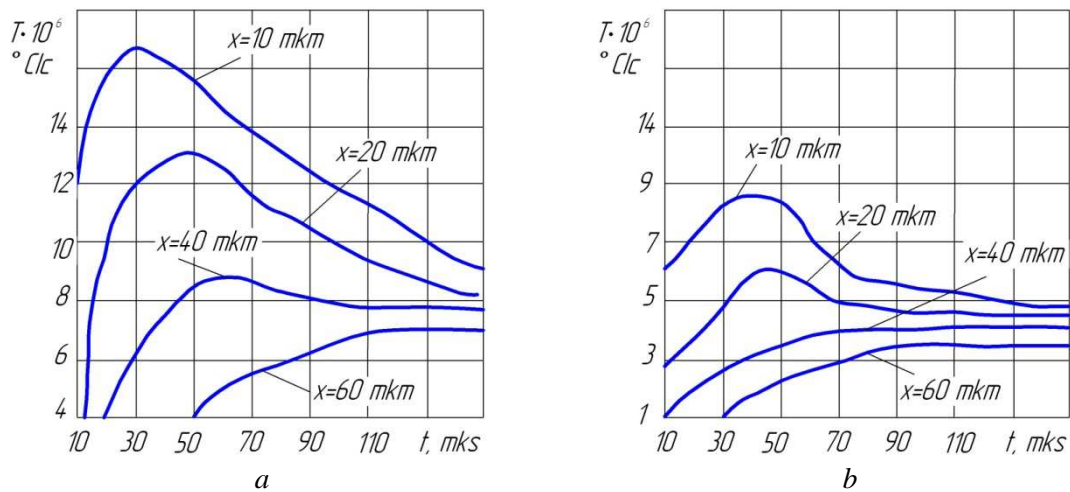
As the result of calculations, let us find  $q_m = 1.5 \cdot 10^{-5} \text{ W/m}^2$  and  $q_c = 1.5 \cdot 10^5 \text{ W/m}^2$ .

Figure 1 depicts the nature of temperature distribution in the grain for given machining modes. Depending on time of contact of the grain with material, thermal working conditions differ from each other. Thus, the peak value of temperature is higher than during multistep grinding; the depth of expansion is greater. For example, the temperature of  $T = 500^\circ\text{C}$  spreads to the depth of 100 microns during creep-feed grinding, as for multistep grinding, it spreads to the depth of 50 microns; consequently, the depth of heating grain during creep-feed grinding is greater.

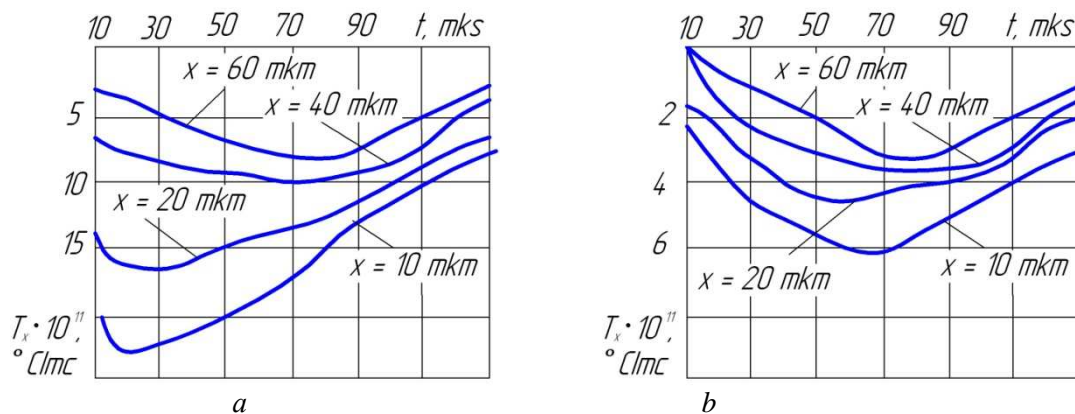


**Figure 1.** The nature of temperature distribution in grain depending on time (*a, b* – multistep and creep-feed grinding)

Due to abrasive grain being sensitive to temperature heterogeneities and because of different parts of grain being heated to different depth, other important performance indicators are temperature variation speed and its gradient. Calculations show that the speed of the thermal process in creep-feed grinding is 2-3 times lower than in multistep grinding; the gradient reduces 3-4 times (fig. 2,3).



**Figure 2.** Speed distribution dependence of thermal processes on time (*a, b* – multistep and creep-feed grinding)



**Figure 3.** Thermal processes speed gradients (*a, b* – multistep and creep-feed grinding)

The whole analysis of the temperature field (temperature, heating and cooling speeds, thermal processes gradients) allows us to give reasoned evaluation for each way of machining and to identify the most optimal variant. The analysis of machining methods showed that creep-feed grinding ensures a greater depth of grain heating, the smaller heating rate and the reduced velocity gradient. It decreases probable allotropic modifications and prevents from occurring of heat strokes - cracking of grains due to high temperature falls. Consequently, it is necessary to employ creep-feed grinding to increase the efficiency of abrasive tool employing.

To confirm the reliability of theoretical assumptions that thermal tension of abrasive grains during creep-feed grinding is lower than in case of multistep grinding, the indirect method of analysis of changes in the structure was used [3].

The microstructure of grains extracted from binding by means of recuperation was studied by using a microscope after samples having been grinded for three minutes. Wear and destruction of diamond grains in the grinding process were determined to occur in several stages; the main ones include opening, abrasive wear due to microcutting and destruction under the action of temperature. For diamond grains in the grinding wheel operating in the multistep grinding mode, it is more likely to destruct under exposure to temperature stresses which is expressed in a cellular construction of the work surface. This structure is usually observed during local destruction of diamond crystals under exposure to temperature stresses along interatomic bonds.



During creep-feed grinding, diamond and cubic boron nitride (CBN) grains have areas of wear which usually correspond to abrasive wear and characterize normal operation of the tool in general. The presence of this wear of grains is indicative of their being kept in binding with enough strength as well as their being exposed to lower stress loading. Due to the fact that the most of cutting edges have considerable occurrence depth, they can only remove swarf of small thickness  $a_z$ , which is possible in case of a little corner radius of these cutting edges. Little part of cutting edges protruding far above the surface of the binding can remove thicker shavings. In abrasive wheel the most of grains of considerable occurrence depth cannot cut the material efficiently due to big values radius of rounding of tops  $\rho$ . It just skims across the surface or deforms the surface plastically. Due to their being highly sharp, grains of diamond and CBN wheels will work with lower loading when removing swarf from machined material. In addition, plastic deformations and heat release shall be considerably reduced.

The analysis of the cutting surface of the diamond or CBN wheels enabled us to make another fundamentally important conclusion: considerable parts of binding of the wheel are in contact with the machined surface during the operation process. If the nature of binding material or its filler turns out to be kindred to material (metallic powder-steel) to be machined; this affinity may cause certain physical-chemical interaction between them. Considerable friction can occur in the contact area of binding. Friction of binding is a source of additional heat generation which is not related to the cutting operation. From the point of view of heat removal, the contact surface of the wheel with the surface to be machined will be extremely heterogenous, since the diamond takes removes heat away more intensively than the binding. As the result, nonuniform temperature conditions may occur in different areas of the surface to be machined. In some cases to increase the efficiency of diamond or CBN grinding, compulsory eliminating the contact of wheel binding and material to be machined is necessary.

Depending on grinding conditions and characteristics of the abrasive tool, grinding wheels work in different modes: blunting, self-sharpening, emergency wear. Also, wheels can work in one mode or with transition from one to another.

Blunting is caused by changing of shape and state of cutting grains with occurrence of wear areas. As the grinding wheel gets blunted, tangential force  $P_z$  increases and, as consequence, temperature of cutting area increases which contributes to phase and structure changes in metal in surface layers as well as occurrence of great tensile stresses. Periodical wheel conditioning is necessary to ensure cutting grains being sharp. Cutting ability of the abrasive wheel is completely restored by removing the blunted layer of abrasive 0.05 – 0.1 mm. The wear of the working part of the wheel during conditioning can become equal to 50%. Blunting ensures high geometric accuracy of surface to be machined but it permits linear wear of the tool equal to  $7 \div 10$  microns.

Diamond and CBN grinding can ensure self-sharpening of the grinding wheel resulting in constant renewal of wheel working part. Self-sharpening permits stabilization of metal removal speed and providing low surface roughness and thickness of metal layer removed for one working travel. Conditioning during grinding process becomes unnecessary. In order to ensure self-sharpening of the grinding wheel, it is necessary to apply softer wheels or to change the cutting mode so as to increase the cutting forces. It is reached by increasing longitudinal feed, depth and width of grinding, as well as decreasing the wheel rotation velocity. The transition from the blunting mode to self-sharpening of the grinding wheel represents sharp intensification of wear of the grinding wheel, increasing its cutting ability and stabilization of intensification of metal removal.

On the basis of tasks of reducing thermal tension, providing quality of the grinded surface and increasing the output capacity of the grinding process, operation of abrasive tool during blunting and emergency wear is not acceptable. The operation of the wheel in a full self-sharpening mode corresponds to solution of tasks set. The full self-sharpening mode is characterized by constant restoring of cutting ability of the wheel, smaller tendency to burns, however, this mode causes more intensive wear of the wheel than the blunting mode.

High-speed grinding with cutting speeds equal to 50 mps increases the speed of metal removal  $5 \div 10$  times if required parameters of accuracy and quality are provided. However, transition to high

speeds is not always reasonable because increasing speed is entailed by increasing contact temperature, vibrations, cyclic loads applied to the wheel. For instance, it is necessary to reduce cutting speed to 20 mps during grinding of steels which are liable to occurrence of grinding defects. Therefore, implementing high-speed grinding is not advisable for such heat-stressed process as grinding details made of hard-to-machine steels and alloys with strict demands to surface quality. In general, in view of the fact that the grinding process is entailed by complex phenomena connected with grain wear, the quality of the surfaces to be machined and the use of the coolant, the final choice of the speed of the detail should be specified taking into account the tool's durability, the temperature in the contact area and the roughness of the surface being machined.

### 3. Conclusion

Three operation modes of the grinding wheel including blunting, full self-sharpening, emergency wear and tear are determined as the result of the research on evaluation of cutting ability of grinding wheels. Recommendations for working capacity of grinding wheels in each operation mode and with a transition from one mode to another are given. Different dependencies were determined. They include dependencies governing the extent of influence of granularity, difference in height and concentration of grains, geometry parameters of detail to be machined and the grinding wheel on treatment modes and the thickness of layer cutoff by one grain. The changing of wheel characteristics and machining modes results in different cutting ability of the tool.

Results of theoretical research of thermal conditions of the abrasive grain during grinding are given. Results of research show that heat tension of operation of grains and their penetration depth during creep-feed grinding are lower than during multistep grinding.

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