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# Influence of Thermophysical Parameters on the Productivity in Grinding

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**Abstract**—A mathematical model is developed for taking account of temperature constraints in creating the machining cycles for wheel grinding on CNC machines. The proposed model permits decrease in machining time by about 25%.

*Keywords:* grinding, machining cycles, temperature constraints, productivity

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Information technology is employed in manufacturing today (for example, in CNC machines and automatic production shops and stores). At many manufacturing plants, twentieth-century standards are used in specifying the cutting conditions. That limits the effectiveness of the new equipment.

The coefficients and recommended supply in standard documents assume specific machining conditions [1, 2]. Therefore, we need to develop a mathematical model by which to calculate the cutting conditions directly for the required machining conditions.

To that end, Rykalin applied the theory of fast-moving heat sources to grinding [3]. In that theory, a boundary condition of the second kind describes the state of the workpiece cross section in the machining zone: its heating in the grinding zone; and its cooling by the working fluid outside that zone. A boundary condition of the third kind describes the state of the workpiece cross section after leaving the machining zone.

A nonlinear one-dimensional formula describing the temperature distribution in surface and deep layers of the workpiece within the wheel–workpiece contact zone may be developed on the basis of [4]. This dependence allows the varying residual temperature in the workpiece after grinding to be taken into account.

After random generation of the tool's working profile, a stochastic model of the temperature field was developed in [5].

The heat flow to the workpiece conforms to a normal distribution, according to experiments in ordinary grinding conditions in [6, 7].

In calculating the temperature, the critical factor is the energy division, according to [8]. The energy division is understood to be the distribution of the heat liberated in machining between the workpiece, the chip, the tool, and the surroundings. In grinding by electrocorundum wheels, 60–85% of the energy goes to the workpiece. The corresponding analytical models take account of all the aspects of the energy distribution between the wheel and workpiece but provide no means of controlling this distribution [8].

A theoretical three-dimensional model for the grinding temperature range at each instant of machining was proposed in [9]. It was established that the heat fluxes are not normally distributed along the width of the grinding wheel and are discontinuous in the direction of workpiece supply.

We see that grinding theory permits relatively high-level calculations and profound understanding of grinding operations. Nevertheless, none of the available models takes account of the temperature field as the margin is decreased. That hinders the development of the optimal grinding cycle.

In particular, if we calculate the radial supply corresponding to the total margin to be removed and use the result throughout the machining process, the temperature front will penetrate into the depth of the workpiece as the margin is removed. That leads to the formation of a defective surface layer on the part produced. Consequently, the part will be rejected. If the supply is calculated for each workpiece rotation, the radial supply over the whole grinding cycle (at high temperature) will be constant and minimal. That will result in low productivity.

Accordingly, we propose the following approach: the supply is calculated in the course of machining;

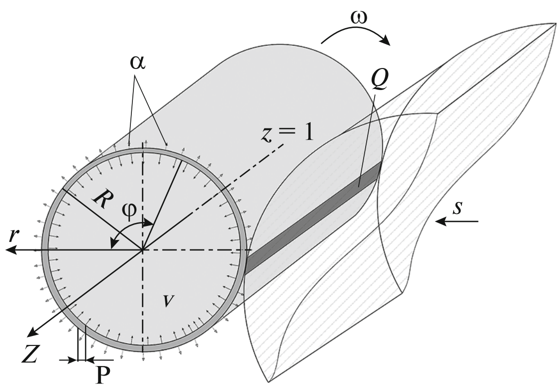


**Fig. 1.** Calculation of the thermal conductivity.

and the limiting temperature is that at the workpiece surface.

Consider a workpiece of radius $R$ (m), specific heat $c$ (J/m$^3$ °C), and thermal conductivity $\lambda$ (J/m s °C). It is a cylinder of unit height with heat-insulated ends. A heat source of power $Q$ (J/m$^2$ s) acts on the workpiece as it moves through the cutting zone (over the contact arc) at angular velocity $\omega$ (rad/s). Beyond the region of action of the heat source with the machined surface, we note heat transfer with coefficient $\alpha$ (J/m$^2$ s °C); within the workpiece, the heat-transfer coefficient is $\nu$ (J/m$^3$ s °C). We obtain a two-dimensional thermophysical problem corresponding to Fig. 1.

To develop the mathematical model for the temperature in the wheel–workpiece contact area, we write the heat-conduction equation in polar coordinates

$$C\frac{\partial U}{\partial t} = \frac{\partial}{\partial r}\left(\lambda\frac{\partial U}{\partial r}\right) + \frac{\lambda\partial U}{r\partial r} + \frac{\partial}{r^2\partial\varphi}\left(\frac{\lambda\partial U}{\partial\varphi}\right), \qquad (1)$$

where $r$ is the radius, m; $\varphi$ is the polar angle; $t$ is the time, s; and $U$ is the temperature, °C.

The boundary conditions are as follows:

- at the contact spot (when $r = R$): $\lambda\frac{\partial u}{\partial r} = Q$;
- beyond the contact spot (when $r = R$): $\lambda\frac{\partial u}{\partial r} = \alpha(T - U)$, where $T$ is the ambient temperature, °C.

The physical parameters of the material depend on the temperature, as established in [10]. The temperature dependence of the specific heat and thermal conductivity was determined in [4]. Those results are used in the present model.

In calculating the power of the heat source, the heat liberation due to plastic shear and friction at the tip of the abrasive grain is taken into account, as in [4]

$$Q_{\text{me}} = \frac{0.8649\sigma_i v_{\text{wh}}\left(1.5a + 0.017l_{\text{bl}}\right)}{0.56a + 0.17l_{\text{bl}}},$$

где $\sigma_i$ is the effective deformational resistance of the material, J/m; $v_{\text{wh}}$ is the wheel speed, m/s; $l_{\text{bl}}$ is the blunting length of the grain, m ($l_{\text{bl}} = 0.1$ mm); and $a$ is the cut thickness, m.

In the calculations, we use the numerical values of $\sigma_i$ for 40 grades of steel from [5].

In grinding, working fluid is supplied to the machining zone. However, because of the high grinding speed, the working fluid does not penetrate into the wheel–workpiece contact zone, as shown in [11–14]. The workpiece surface is cooled on leaving the contact zone. To find the heat transfer when the machined surface interacts with the turbulent flux of working fluid, we use the formula from [11].

To simplify the calculation, we need to introduce the thermal conductivity within the differential. Therefore, we introduce the function $G = \int_0^u \lambda(\theta)\partial\theta$.

Thus, in two dimensions, we obtain a mixed boundary condition for Eq. (1).

Determining the stability of the calculations usually reduces to establishing the relation between the increments in time and space. In the present case, if $\Delta r$ is the radial increment and $\Delta\varphi$ is the angular increment, the calculation will be stable if

$$\Delta t < \frac{c\left(r\Delta r\Delta\varphi\right)^2}{2\lambda\left(\left(\Delta r\right)^2 + r\Delta\varphi\right)^2}. \qquad (2)$$

We assume that we need to increase the precision of the solution by formal decrease in the grid increments $\Delta r$ and $\Delta\varphi$. Then we must also decrease $\Delta t$ so that Eq. (2) is satisfied. This constraint is not applicable in the present case. Therefore, Eq. (2) is solved by a differential difference method [15].

Introducing the new variable $s = r^2$ so as to decrease the errors due to difference in the areas, we write the heat-conduction equation in the form

$$\frac{c\partial G}{\lambda\partial t} = 4s\frac{\partial^2 G}{\partial s^2} + 4\frac{\partial G}{\partial z} + \frac{\partial^2 G}{z\partial\varphi^2}.$$

Correspondingly, the boundary conditions take the form

$$\frac{\partial G}{\partial s} = \frac{1}{2\sqrt{s}}Q; \text{ and } \frac{\partial G}{\partial s} = \frac{\alpha}{2\sqrt{s}}\left(T - u(G)\right).$$

The distribution of grains in the wheel is simulated for the given number of sections (in terms of the contact length).

At present, two types of wheel–workpiece contact are considered in the literature: 1) continuous contact [6, 8, 11]; 2) discontinuous contact [4, 5, 9]. Calculations for discontinuous contact give precise data regarding the grinding process but require considerable computational power. Calculations for continuous contact diverge from experimental data by no more than 15%, and the computations are much shorter. To increase the computation rate in the model, we consider continuous wheel–workpiece contact, taking account of the wheel wear.

The grinding cycle is formulated as follows. The initial data include not only the characteristics of the wheel and workpiece but also the maximum radial supply $s_{max}$ in the machine tool, its increment $\Delta s$, and the number of sections for temperature calculation. If the temperature at the final surface of the part approaches the critical value in section $n$, the calculation reverts to section $n - 1$, where the supply is decreased. If there are no scorch marks with the new supply, calculation of the cycle continues. Otherwise, the procedure is repeated.

To verify the effectiveness of the model, we compare the machining time for standard conditions and for the proposed model.

In the comparison, we consider a shaft in which a pin of diameter 60 mm and width 10 mm is to be machined. The tool diameter is 400 mm; its speed is 35 m/s; and the margin to be removed is 0.5 mm.

A two-step cycle is obtained on the basis of the calculation in standard [1]: $s_1$ = 0.78 mm/min and $s_2$ = 0.07 mm/min. The basic machining time $T_b$ = 0.573 min.

According to the proposed model, the cycle has three steps: $s_1$ = 1.25 mm/min, $s_2$ = 0.95 mm/min, and $s_3$ = 0.65 mm/min. The basic machining time $T_b$ = 0.461 min. The new cycle permits 24% increase in efficiency.

## CONCLUSIONS

(1) We have developed a model taking account of the temperature constraints in calculating the machining cycles for grinding by an abrasive wheel.

(2) The number of steps in the machining cycle is determined automatically on the basis of avoidance of critical temperatures at the surface of the finished product. The new cycle permits 24% increase in efficiency in comparison with the standard method in [1].

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