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# Temperature Fields in Grinding by Abrasive Wheels

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**Abstract**—A method is proposed for calculating the temperatures at the surface of the workpiece and within its interior on grinding by abrasive wheels of different design (discontinuous, composite, or hybrid wheels). On that basis, the temperature fields in the cutting zone are calculated.

*Keywords:* grinding, discontinuous grinding wheels, composite grinding wheels, hybrid wheels, mean contact temperature, workpiece temperature
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In high-tech manufacturing, considerable attention is paid to the machining quality and, in particular, the state of the surface layer, which is characterized by the depth and degree of cold working, the residual stress, the structure of the workpiece, its phase state, and so on. Despite technological inheritance, the final state of the surface layer mainly depends on the finishing operations, such as grinding.

Surface defects—scorch marks and microcracks—are often formed in the grinding of high-carbon, blister, and high strength steels and titanium and other alloys. Such defects are generally impermissible, for the following reasons.

(1) They are associated with residual tensile stress in the surface layer, reducing the fatigue strength.

(2) The microcracks formed give rise to fatigue cracks if alternating loads are applied to the part.

To eliminate scorch marks and microcracks, grinding wheels with an interrupted cutting surface—specifically, discontinuous, composite, or hybrid wheels—are often used in high-speed production. The working surface of discontinuous wheels takes the form of alternating cutting projections and troughs. For composite wheels, the troughs on the working surface are filled with solid lubricant. Hybrid wheels combine the features of discontinuous and composite wheels. In the lubricating segments of these wheels, troughs precede the cutting projections. By means of such wheels, the temperature may be reduced by 15–40% in comparison with mass-produced wheels with a continuous cutting surface, in identical working conditions [1].

Note that, in order to ensure the elimination of grinding defects in the cutting zone, it makes sense to calculate the temperature in the contact zone in selected grinding conditions, at the design stage. Knowing the mean contact temperature $T$ and also the heating rate $v_{he}$ and cooling rate $v_{co}$ of the workpiece in the cutting zone, we may assess the likelihood of structural and phase transformations in the surface layer in the case of metastable phase diagrams [2]. We need an efficient method of determining $T$, $v_{he}$, and $v_{co}$.

To calculate the mean contact temperature in the cutting zone and the heating and cooling rates of the workpiece in grinding by discontinuous, composite, and hybrid wheels, we employ a method based on formulas derived for the operating conditions of a hybrid grinding wheel (Fig. 1). The hybrid wheel includes segments corresponding to discontinuous and composite wheels, and therefore calculation of the workpiece temperature in grinding by continuous, discontinuous, and composite wheels may be regarded as particular cases of calculating the temperature when using a hybrid wheel.

The analytical formulas for the workpiece temperature (K) in grinding by wheels of various types take the following form [3].

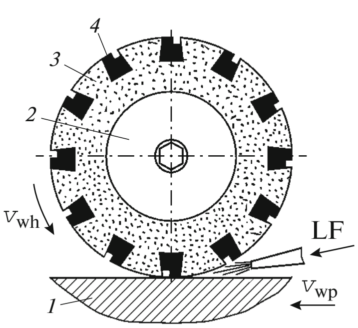


**Fig. 1.** Plane grinding by a hybrid wheel: (*1*) workpiece; (*2*) hybrid wheel; (*3*) cutting projection; (*4*) lubricant segment; LF, lubricant fluid.

At the workpiece surface

$$T(t,x,0) = -\frac{1}{4\pi\lambda}\int_0^t \frac{d\tau}{\tau}\int_{-\infty}^{\infty} dx'\left[b(x',t-\tau)T(t-\tau,x',0) + d(x',t-\tau)\right]\exp\left[-\frac{(x'-x-v_{\rm wp}\tau)^2}{4a\tau}\right].$$

Within the workpiece

$$T(t,x,y) = \frac{1}{4\pi}\int_0^t \frac{d\tau}{\tau}$$

$$\times\int_{-\infty}^{\infty} dx'\left[\left(\frac{y}{2a\tau} - \lambda^{-1}b(x',t-\tau)T(t-\tau,x',0) - \lambda^{-1}d(x',t-\tau)\right)\right]\exp\left[-\frac{(x'-x-v_{\rm wp}\tau)^2 + y^2}{4a\tau}\right].$$

Here $T = T(t, x, y)$ is temperature, K, $t$ is the time, s; $x$, $y$ are the coordinates, m; $a$ is the thermal diffusivity, m$^2$/s; $v_{\rm wp}$ is the speed of the workpiece, m/s; $\lambda$ is the thermal conductivity, W/(m K); $x'$ and $\tau$ are variables.

The form of the functions $d(x,t)$ and $b(x,t)$ will depend on the structure of the wheel. For example, for a hybrid wheel

$$d(x,t) = -qf(t)\Theta(\delta - x)\Theta(x), \quad (1)$$

where

$$f(t) = \sum_{n=0}^{\infty}\Theta(nt_{\rm cy} + t_p - t)\,\Theta(t - nt_{\rm cy}).$$

In Eq. (1), $q$ is the heat flux density, W/m$^2$; $\Theta(z)$ is a Heaviside step function

$$\Theta(z) = \begin{cases} 1 & \text{when} \quad z \ge 0 \\ 0 & \text{when} \quad z < 0 \end{cases}.$$

Likewise, we may express $b(x,t)$ as a linear combination of Heaviside functions

$$\begin{aligned} b(x,t) &= \alpha_{\rm fl}\Theta(-x) + \alpha_{\rm fl}\Theta(x-\delta) \\ &+ \alpha_{\rm sol}\Theta(\delta - x)\Theta(x)\sum_{n=0}^{\infty}\Theta(nt_{\rm cy} + t_{\rm p} + t_{\rm so} - t)\Theta(t - nt_{\rm cy} - t_{\rm p}) \\ &+ \alpha_{\rm fl}\Theta(\delta - x)\Theta(x)\sum_{n=0}^{\infty}\Theta((n+1)t_{\rm cy} - t)\,\Theta(t - nt_{\rm cy} - t_{\rm p} - t_{\rm so}), \end{aligned} \quad (2)$$

where $\alpha_{\rm fl}$ is the heat-transfer coefficient between the machined workpiece surface and the lubricant fluid, W/(m$^2$ K); $\alpha_{\rm sol}$ is the heat-transfer coefficient between the machined workpiece surface and the solid lubricant segments, W/(m$^2$ K); $t_{\rm cy}$ is the cycle time, s; $t_{\rm p}$ is the contact time of the cutting projection and the workpiece, s; $t_{\rm so}$ is the contact time of the lubricant segment and the workpiece, s; $\delta$ is the length of the contact zone between the wheel and the workplace, m.

Taking account of Eqs. (1) and (2), we may write analytical formulas for the temperatures at the surface of the workpiece and within its interior on grinding by a hybrid wheel in the following form.

At the workpiece surface

$$T^{(1)}(t,x,0) = T^{(0)}(t,x,0)$$

$$-\frac{1}{4\pi\lambda}\int_0^t \frac{d\tau}{\tau}\int_{-\infty}^{\infty} dx' b(x',t-\tau)T^{(0)}(t-\tau,x',0)\exp\left[-\frac{(x'-x-v_{\rm wp}\tau)^2}{4a\tau}\right].$$

Within the workpiece

$$T^{(1)}(t,x,y) = T^{(0)}(t,x,y)$$

$$+\frac{1}{4\pi}\int_0^t \frac{d\tau}{\tau}\int_{-\infty}^{\infty} dx'\left[\left(\frac{y}{2a\tau} - \lambda^{-1}b(x',t-\tau)\right)T^{(0)}(t-\tau,x',0)\right]\exp\left[-\frac{(x'-x-v_{\rm wp}\tau)^2 + y^2}{4a\tau}\right],$$

where

$$T^{(0)}(t,x,y) = \frac{q}{4\lambda}\sqrt{\frac{a}{\pi}}$$
$$\times \int_0^t \frac{d\tau}{\sqrt{\tau}} \exp\left[-\frac{y^2}{4a\tau}\right]\left[\operatorname{erf}\left(\frac{\delta - x - v_{\mathrm{wp}}\tau}{2\sqrt{a\tau}}\right) + \operatorname{erf}\left(\frac{x + v_{\mathrm{wp}}\tau}{2\sqrt{a\tau}}\right)\right] f(t-\tau);$$

$$T^{(0)}(t,x,0) = \frac{q}{4\lambda}\sqrt{\frac{a}{\pi}}\int_0^t \frac{d\tau}{\sqrt{\tau}}\left[\operatorname{erf}\left(\frac{\delta - x - v_{\mathrm{wp}}\tau}{2\sqrt{a\tau}}\right) + \operatorname{erf}\left(\frac{x + v_{\mathrm{wp}}\tau}{2\sqrt{a\tau}}\right)\right] f(t-\tau).$$

To determine the temperatures for grinding by continuous, discontinuous, or composite wheels, we simply substitute the appropriate expressions for $b(x,t)$ and $d(x,t)$.

The analytical formulas obtained for the nonsteady temperature fields in grinding by different wheels may be incorporated in the corresponding software.

On the basis of the proposed method and the corresponding software, we may calculate the temperature fields in the cutting zone when grinding by means of wheels of different structure. In Fig. 2, we show the resulting temperature fields in annular samples of 30ХГСН2А and 15Х12Н2МВФАБ-Ш steel and VT20 titanium alloy, in coordinates associated with the contact zone. The temperature fields in rings of 30ХГСН2А steel are calculated for external grinding by continuous, composite, or hybrid wheels (Figs. 2a–2c). The fields in rings of 15Х12Н2МВФАБ-Ш steel are calculated for internal grinding by continuous and composite wheels (Figs. 2d and 2e), and those in rings of VT20 titanium alloy are calculated for internal grinding by continuous and discontinuous wheels (Figs. 2f and 2g).

Research shows that the discrepancy between the analytical values for the mean contact temperature and values measured by a thermocouple is no more than 10% [4].

On the basis of the calculated temperature fields (Fig. 2), the heating and cooling rates of the workpiece may be calculated. Knowing the temperature distribution in the surface layer of the workpiece, the heating and cooling rates, and the holding time at high temperature, we may assess the likelihood of structural and phase transformations in the material.

However, for specified grinding conditions, that requires the use of metastable phase diagrams, since metastable structures are formed at the heating rates typical of grinding. The critical points for such structures may be displaced significantly with respect to the known equilibrium diagrams. For example, if the heating rate of quenched steel is increased, the critical point $A_{c1}$ will be lower, according to the data in [5].

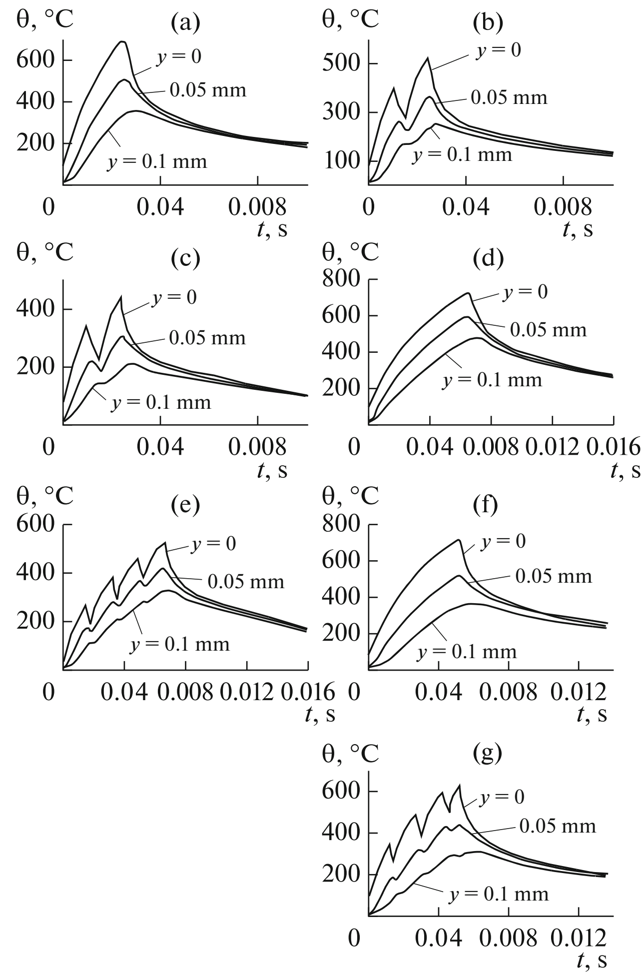


**Fig. 2.** Temperature fields in the contact zones of 30ХГСН2А steel samples with wheels of different structure in external grinding (a–c); and the contact zones of 15Х12Н2МВФАБ-Ш steel samples (d, e) and VT20 titanium-alloy samples (f, g) with wheels of different structure in internal grinding: (a, d, f) continuous wheel; (b) hybrid wheel; (c, e) composite wheel; (g) discontinuous wheel. Grinding conditions: (a–c) PP300×127×32 25A25SM27K5 wheel; $v_{\mathrm{wh}}$ = 30 m/s; $v_{\mathrm{wp}}$ = 30 m/min; $s_{\mathrm{lo}}$ = 0.5 m/min; $s_{2x}$ = 0.03 mm/double pass; (d, e) PP100×20×25 25A25M37K5 wheel; $v_{\mathrm{wh}}$ = 30 m/s; $v_{\mathrm{wp}}$ = 27 m/min; $s_{\mathrm{lo}}$ = 1 m/min; $s_{2x}$ = 0.0075 mm/double pass; (f, g) PP100×20×25 63S25M36K5 wheel; $v_{\mathrm{wh}}$ = 34 m/s; $v_{\mathrm{wp}}$ = 32 m/min; $s_{\mathrm{lo}}$ = 0.5 m/min; $s_{2x}$ = 0.01 mm/double pass.

## CONCLUSIONS

We have developed a method of calculating the temperature fields at the surface of the workpiece and within its interior on grinding by abrasive wheels of different design (discontinuous, composite, or hybrid wheels). On that basis, the mean contact temperature in the cutting zone may be determined, as well as the heating and cooling rates of the workpiece. By that means, the temperature fields in the cutting zone on grinding are calculated.

That allows us to assess the likelihood of structural and phase transformations in the material in specified cutting conditions.

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