TEMPERATURE FIELDS IN AN ABRASIVE TOOL

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The finite differences method is used to calculate the temperature fields in an abrasive disk as a function of grinding conditions.

As a rule, the heat generated in the chip-formation zone during grinding has an adverse effect on the efficiency of the grinding operation, the quality of the surfaces of the part being ground, and the cutting ability of the abrasive tool. It is known [1, 2] that the thermal activity of contacting bodies depends to a considerable extent on their mutual velocities and the ratios of their thermophysical characteristics. It follows from an analysis of oscillograms depicting the change in temperatures on an abrasive grain [3] that the regime of thermal saturation in the grain begins after a very short period of loading. The grain actively removes heat from the cutting zone only during this period. The grain's thermal activity drops sharply when the thermal saturation regime is reached, which depends on the geometric dimensions of the contact region and the grinding speed.

Considering that the increasingly stringent requirements of industry in regard to machining efficiency are tending to increase grinding speeds, it is important to analyze the effect of the kinematics of grinding and the thermophysical properties of the abrasive tool on the thermal state of the tool.

Here, we calculate the temperature fields in an abrasive disk with allowance for the cyclic heating and variable thermophysical characteristics of the tool, the grinding regimes, the geometric dimensions of the contact zone, and the ratio of heating time to cooling time for different heat-transfer coefficients. During grinding, the disk is subjected to the cyclic action of a heat source: heating in the zone of contact with the workpiece and cooling outside this zone.

Established formulas [1] describe the propagation of heat for the case when the disk completely loses its heat during the cooling period. In this case, the boundary conditions will be the same for all grinding cycles. Otherwise, formulas based on the scheme of a single loading by the heat source are valid only for the first grinding cycle. The second and subsequent cycles have their own characteristic boundary conditions. However, in actual grinding operations, there is not sufficient time for thermal processes to stabilize during one disk revolution even in the presence of cooling.

When solving the differential equation of heat conduction in calculations of the temperature fields created during multiple heatings, it is necessary to consider the following features of the actual grinding process. First of all, the boundary conditions change with the advent of each successive cooling stage, and each subsequent problem must be examined as a continuation of the previous problem. Secondly, the initial conditions for each subsequent problem should be the solution of the previous problem at the moment one stage is replaced by another. The problem being examined here is solved in the following formulation [4]:

$$\frac{\partial T_1(x,\ \tau)}{\partial \tau} = a\frac{\partial^2 T_1(x,\ \tau)}{\partial x^2},\quad 0 \leqslant x < \infty;\quad 0 \leqslant \tau < \tau_1;$$

$$T_1(\infty,\ \tau) = T_0;\quad T_1(0,\ \tau) = T_c = \text{const};$$

$T_1(x,\ 0) = T_0$ (at the beginning of the calculation); $T_1(x,\ 0) = f(x)$ (with repetition of the cycles), where $f(x)$ is the temperature field obtained at the end of the preceding period;

cycle II (cooling):

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$$\frac{\partial T_2(x,\ \tau)}{\partial \tau} = a\,\frac{\partial^2 T_2(x,\ \tau)}{\partial x^2},\quad 0 \leqslant x \leqslant \infty;\quad 0 \leqslant \tau \leqslant \tau_2;$$

$$\frac{\partial T_2(0,\ \tau)}{\partial x} = \frac{\alpha}{\lambda}\,[T_2(0,\ \tau) - T_0];\quad T_2(\infty,\ \tau) = T_0;\quad T_2(x,\ 0) = \varphi(x),$$

where $\phi(x)$ is the temperature field at the end of the preceding heating period;

cycle III (heating):

$$\frac{\partial T_3(x,\ \tau)}{\partial \tau} = a\,\frac{\partial^2 T_3(x,\ \tau)}{\partial x^2};\quad T_3(\infty,\ \tau) = T_0;\quad T_3(0,\ \tau) = T_c = \text{const};$$

$$T_3(x,\ 0) = T_2(x,\ \tau_2).$$

In the above scheme, boundary conditions of the first kind are adopted in the heating cycle. Such a choice is justified by the following consideration. According to research in metal physics, the melting point is reached in the deformation zone [5]. In regard to grinding, it was established experimentally in [3, 6] that the melting point of the material of the workpiece is reached on the grains of the disk. Thus, as a first approximation we assume that the temperature on the surface of the body in question is known and is equal to the melting point of the material being ground. As a result, the first and third boundary-value problems of heat conduction alternate in the chosen theoretical scheme. The steady-state regime is established a certain amount of time after the beginning of grinding. In this regime, the next pairwise cycle (heating—cooling) will repeat the preceding cycle, i.e., the process of heat accumulation ends and thermal saturation takes place. The foregoing scheme for calculation of the temperature field, taking into account the multiple heatings and heat accumulation, makes it possible (in contrast to the formulation with a single heating) to study the transient period, determine the duration of this period, and establish the amount of heat accumulated as a function of the grinding conditions.

The scheme is based on a unidimensional heat-conduction equation. The validity of this approach was checked by analyzing data obtained by the method of electrothermal analogy on a two-dimensional electrical network model. The results showed that the size of the error decreases with an increase in the depth of the point being studied and the velocity of the heat source and a decrease in the thermal conductivity of the test material. It was found that when a metal part is being ground and the velocity of the heat source ranges up to 12 m/min, the error in the contact zone is 2.7%. At a depth of 0.2 mm or more, the corresponding error is 0%. In practice, the velocity of the heat source over the working surface of the disk is at least 30 m/sec, while the thermal conductivity of the abrasive tool is substantially less than the thermal conductivity of the metal being ground. Thus, with allowance for the dimensions of the surface being ground — which are considerably greater than the dimensions of the surface being ground — which are considerably greater than the dimensions of the heat source — we can justifiably use a unidimensional formulation of the thermal problem in calculating the temperature fields in an abrasive disk. The stated boundary-value problem was solved with the use of an implicit grid method [7].

Having chosen variable time and space steps for the grid and having replaced the derivatives by finite differences, we reduce the heat-conduction equation to the following form:

$$\frac{T_{i,j+1} - T_{i,j}}{m} = a\,\frac{T_{i+1,j+1} - 2T_{i,j+1} + T_{i-1,j+1}}{h}$$

with $i = 1, 2, \ldots, n - 1$; $j = 0, 1, 2, \ldots$, where m and h are the time and space steps of the grid, respectively.

The time step of the grid was $1 \cdot 10^{-4}$ sec during the heating period and $5 \cdot 10^{-4}$ sec during the cooling period. The size of the step for the space variable was chosen in relation to the depth of the point being studied; the step was 0.2 mm within the range up to 2 mm, 0.5 mm in the range 2-7 mm, and 1 mm above 7 mm.

The resulting system of linear equations was solved by the trial-run method on an ES-1020 computer. The condition of stabilization of the heating process was a difference of no more

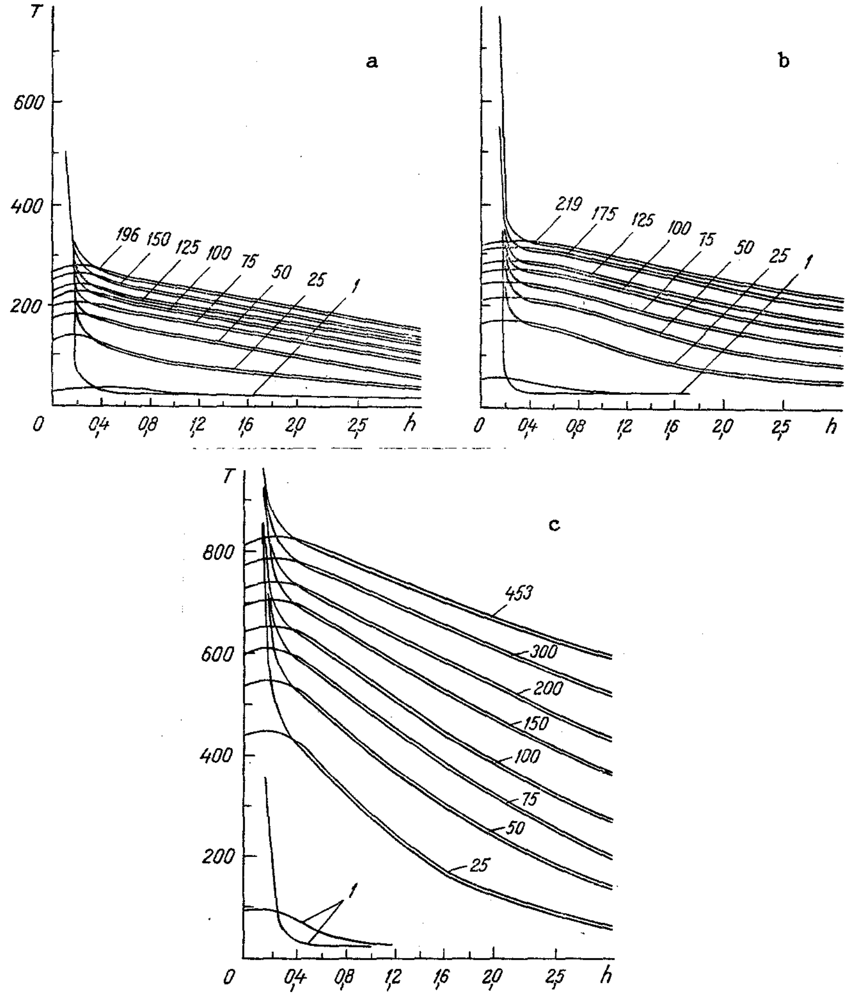

Fig. 1. Distribution of the temperature fields in an abrasive disk in relation to the cyclicity of the heating and the grinding conditions: a) D = 500 mm, ℓ = 15 mm, v = 50 m/sec, τ_1 = 0.0003 sec, τ_2 = 0.031 sec, n_{stab} = 196 cycles; b) D = 330 mm, ℓ = 15 mm, v = 33 m/sec, τ_1 = 0.0005 sec, τ_2 = 0.047 sec, n_{stab} = 219 cycles; c) D = 260 mm, ℓ = 40 mm, v = 26 m/sec, τ_1 = 0.0015 sec, τ_2 = 0.030 sec, n_{stab} = 453 cycles; the numbers next to the curves denote the number of pairwise heating–cooling cycles.

than 0.5 °C in the temperatures of adjacent cycles. The temperature fields were calculated for abrasive disks on a bakelite binder. The disks had thermal conductivities of 2 and 4 W/(m·K), a heat capacity of 400 J/(kg·K), and a density of $2.8 \cdot 10^3$ kg/m³. The heat-transfer coefficients were 200, 300, and 500 W/(m²·K). The heating time for each point of the working surface of the disk during one of its rotations (one cycle) was determined from the relationship between the length of the contact arc and the frequency of disk rotation and was 0.0155-0.047 sec. The ratio of the heating time to the cooling time fluctuated within the range 0.00965–0.153 and embraced the conditions typical of plane grinding, cutting of parts, and sharpening of the tool.

It was established as a result of calculations that thermal processes do not stabilize in the abrasive disk during one rotation (pairwise heating–cooling cycle) under the investigated conditions. Instead, heat builds up over several cycles. This is expressed in an increase in the temperature of the surface layers and the depth of the heat-affected zone. A steady-state regime is established in the disk a certain time after the beginning of grinding. Here, the next pairwise cycle repeates the previous cycle to within the 0.5 °C specified by the program. Beginning with this moment, the estabished temperature field, having reached a certain depth, begins to be displaced toward the center of the disk at the rate at which the disk wears. The stabilization time (the time required to reach the steady-state regime), the depth of heating during this time, and the maximum heating temperature all depend in this case on

TABLE 1. Calculated Values of the Coefficient k and the Stabilization Time (n_{stab}) in Relation to the Grinding Conditions

Grinding conditions					Calculated values	
D	l	v	τ_1	τ_2	$k=\frac{\tau_1}{\tau_2}$	n_{stab}
260	40	50	0,0008	0,0155	0,0516	459
260	40	26	0,0015	0,030	0,0500	453
500	40	50	0,0008	0,0306	0,0261	364
330	15	33	0,0005	0,047	0,0106	219
500	15	50	0,0003	0,031	0,0097	196
500	15	75	0,0002	0,0207	0,0097	182
500	15	100	0,00015	0,0155	0,0096	99

the ratio of the contact and noncontact periods, other conditions (thermophysical characteristics, heat transfer, etc.) being equal.

Figure 1 shows the temperature fields in an abrasive disk 500 mm in diameter on a bakelite binder (λ = 2 W/(m·K); c = 400 J/(kg·K); γ = 2800 kg/m^3) in the case of plane machine grinding. The heat-transfer coefficient in the noncontact period α = 300 W/(m^2·K). The ratio of the durations of the contact and noncontact periods (k) changed due to a reduction in the diameter of the disk as it wore and an increase in the length of the contact arc (such as is seen in the rough grinding of rolled products). Thus, in the use of a tool with a diameter D = 500 mm at a velocity v = 50 m/sec, the coefficient k, equal to the ratio τ_1/τ_2, takes the value 0.00968 (Fig. 1a).

At D = 300 mm and v = 33 m/sec, k = 0.01064 (Fig. 1b). For a disk worn the maximum amount (D = 260 mm) and operating at a velocity of 26 m/sec, k = 0.050 (Fig. 1c).

It should be noted that the temperature and depth of heating of the disk increase with an increase in the ratio k. The greater k, the longer the period of nonsteady heating. Thus, with k = 0.00968, stabilization of the temperature field beings in the 196th cycle. With k = 0.050, it begins in the 453rd cycle (Table 1). There is also a significant increase in the depth of propagation of heat into the disk. The same result is obtained with an increase in the thermal conductivity of the disk and a decrease in the heat-transfer coefficient.

Direct measurement of temperature with a thermal probe was used to experimentally study the process of heat buildup in the abrasive disk. Here, temperature was measured near the working surface of the disk at certain moments of its operation (with intervals of 10 min). It was found that an increase in the operating time of the disk, i.e., the number of grinding–cooling cycles was accompanied by an increase in the temperature of its working surface. This is a consequence of the heat buildup. Heat is accumulated even more rapidly as the disk wears, in connection with its loss of mass and the reduction in grinding speed.

The buildup of heat is accompanied by a reduction in the thermal activity of the disk, i.e., a reduction in its ability to remove heat from the cutting zone. This adversely affects the quality of the ground surface. During the experiment, the 7 × 15 mm surface being studied was in constant contact with the end surface of the disk. By varying the position of the specimen relative to the trajectory of the disk grains, we also changed the length of the arc of contact between points of the disk and the workpiece, i.e., the time of heating of the disk surface τ_1. In this case, the pattern of crack formation changed dramatically: with an increase in the length of the arc from 7 to 15 mm, there was a substantial increase in the number of cracks on the ground surface.

The rate of increase in the temperature of the heated part of the disk depends both on the depth of the point under consideration – as shown in Fig. 2 for conditions similar to Fig. 1c – and on the number of cycles. Thus, the surface layers (curve 1) reach thermal saturation very quickly. The temperature of this zone reaches 750°C during the first 100 cycles. It increases by only 100°C during the next 300 cycles and does not increase significantly after the 450th cycle. The latter is indicative of the attainment of thermal equilibrium. The layers of the disk located at a depth of 3.5 mm relative to the working surface are heated to 230°C during the first 100 cycles and to 550°C after 300 cycles (curve 4). Thus, the deeper layers reach thermal saturation more slowly than the surface layers. The

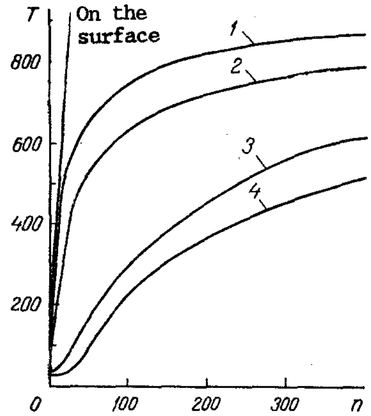

Fig. 2. Rate of heating of the surface layer of an abrasive disk over time with D = 260 mm, v = 26 m/sec, K = 0.95, λ = 2 W/(m·K), $\alpha = 1.8\cdot10^{-6}$ m/sec², and α = 300 W/(m²·K): curves 1, 2, 3, and 4 correspond to the temperatures in the tool 0.2, 0.4, 2.5, and 3.5 mm from the surface, respectively.

penetration of excess temperature to a greater depth — which as also recorded by direct measurement of the temperature on the disk — indicates the presence of heat sinks on the spindle of the machine. This must be taken into account in the mathematical model for a more accurate description of thermal processes. The heating of the working surface of the disk to temperatures considerably in excess of the temperature at which the binder breaks down initiates chemical reactions between components of the disk, the workpiece, and the process medium. The possibility of the occurrence of such processes was determined theoretically from the change in the isobaric-isothermal potential of the chemical reactions. In theoretical studies of the cutting zone, the last-mentioned fact means that it is necessary to introduce a term reflecting the thermal effect of possible chemical reactions into the mathematical model of the heat source. An increase in the number of cycles is accompanied by a reduction in the effect of the cyclicity of the heating on the temperature gradient in the interior of the disk. Thus, for the layers located 3.5 mm from the surface, the difference between the heating and cooling curves is 6.5°C after 25 cycles but only 0.3°C in the saturation regime (after 450 cycles) (see Fig. 1c). In connection with the cyclic nature of the heating, the temperature waves decay exponentially with increasing distance from the surface. This makes it possible to replace the periodic heat flow through the contacting working surface by a constant heat flux in the initial model. The effect of cyclicity increases with an increase in diffusivity. By reducing diffusivity — such as through an increase in the heat capacity of the abrasive material due to the use of special fillers — it is possible to reduce the size of the heat-affected zone and the degree of softening of the disk and to improve the disk's wear resistance. The results obtained here give an idea of the effect of grinding conditions on the thermal state of the abrasive disk and its thermal activity and help solve both the direct problem — optimize cutting regimes using an abrasive tool with specified characteristics — and the inverse problem — calculate the properties required of the disk for specified grinding conditions.

NOTATION

a, diffusivity, m²/sec; τ_1, τ_2, duration of contact (heating) and noncontact (cooling) periods, respectively, sec; T_c, temperature on the surface of contact of an abrasive grain with the metal being ground, °C; $T_{1,2,3}$, temperature of the abrasive disk in the first, second, and third cycles, respectively; T_0, ambient temperature, °C; α, heat-transfer coefficient, W/(m²·K); λ, thermal conductivity of the abrasive disk, W/(m·K); c, heat capacity of the abrasive material, J/(kg·K); γ, density of the abrasive material, kg/m³; D, diameter of the disk, mm; v, grinding speed, m/sec; k, coefficient equal to the ratio τ_1/τ_2; h, depth of the surface layer of the disk, mm; n, number of pairwise heating–cooling cycles; n_{stab}, number of pairwise heating–cooling cycles until stabilization of the disk-heating process; T, temperature of the disk, °C; ℓ, length of the arc of contact of the disk with the workpiece, mm.

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