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GEAR GRINDING TEMPERATURE DETERMINATION

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Annotation *The work is devoted to solving an important scientific and technical problem of determining the gear grinding temperature in profile gear grinding on CNC machines on the basis of the development of subsystems for the designing, monitoring and technological diagnosis of the operation, which allow adapting the elements of the technological system. For this purpose a methodology is developed for researching the technological grinding system using scientific methods of modeling, optimization and control. The software for these subsystems is created on the basis of the mathematical models of the temperature field. It is substantiated the use of a solution of a one-dimensional differential heat equation for gear grinding designing and diagnosis, including taking into account the cooling effect of lubricoolant. On the basis of this solution, a single mathematical model of a grinding temperature cycle is developed.*
Keywords: *profile gear grinding, grinding system, gear grinding temperature, gear grinding modes.*

Among the main requirements for the quality of gears is the lack of grinding burns and microcracks. The quality of the gear surface layer is formed on a gear grinding operation. The most application in modern technologies of grinding were obtained the only two methods: the profile gear grinding and the warm one. The first method is distinguished by higher accuracy (DIN 3-6) with the same performance of these methods, and the second – by higher performance at the same accuracy.

Several works are devoted to the study of thermal phenomena of profiled grinding [1-3]. The solutions presented in these papers are obtained without the formulation of the problem as well as the initial and boundary conditions. The most complete thermal field from the moving strip source is investigated by the author of the source J.C. Jaeger [4,5] and then prof. Yakimov A.V [6] and prof. V.A. Sypailov [7]. However, the classification of similar one-, two- and three-dimensional tasks for determining the gear grinding temperature, and a complex of comparative studies of these solutions for the purpose of determining engineering calculations that are acceptable for engineering purposes, have not yet been fulfilled.

In accordance with the scheme of profiled grinding, the moving heat source has a rectangular shape 1234 (Fig. 1, *a*) and moves in the direction of the axial feed vector at the steady temperature field. Such a thermal circuit can be converted into an equivalent form on the grinding plane (Fig. 1, *b*) in the coordinate system adopted in [6,7].

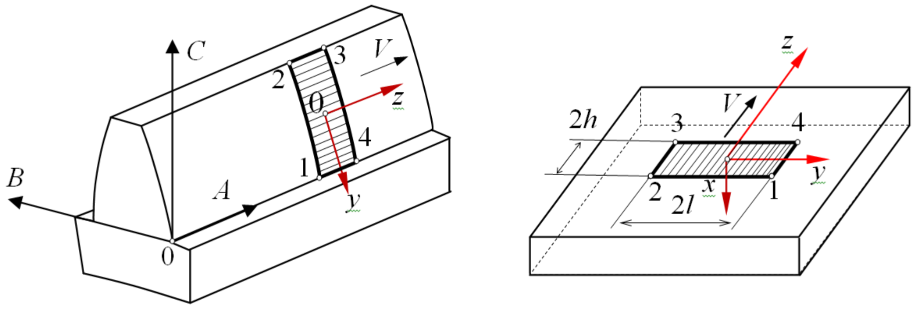

Fig.1. Schematic view of moving real heat source on the grinding tooth (*a*) and the nearest one on the grinding plane (*b*)

The determination of temperature on the basis of moving strip source mathematical model with the restriction of this source along the y axis (Fig. 1, *a*) is a complex task of mathematical thermophysics which was first solved by J.C. Jaeger [7]. The solution of this problem for the determination of the temperature at a constant density of the heat flux on the surface in the contact zone has the following form [7]

$$T(X,Y,Z,L,H)=\frac{2qa}{4\lambda V\sqrt{2\pi}}\int_0^\infty \exp\left(\frac{-X^2}{2u}\right)\left(\Phi\left(\frac{Y+L}{\sqrt{2u}}\right)-\Phi\left(\frac{Y-L}{\sqrt{2u}}\right)\right)\times$$
$$\times\left(\left(\Phi\left(\frac{Z+H+u}{\sqrt{2u}}\right)-\Phi\left(\frac{Z-H+u}{\sqrt{2u}}\right)\right)\right)\frac{1}{\sqrt{u}}du \qquad (1)$$

where q is the intensity or density of the heat flux, W / m^2; a - coefficient of temperature conductivity, m^2 / s; λ is coefficient of thermal conductivity, W / (m ·° C); V is velocity of the source in the direction of the z axis (axial feed), m / s; X, Y, Z are dimensionless or relative coordinates, which correspond to dimensional coordinates x, y, y; H, L are dimensionless half-width (parameter Peclet) and dimensionless half-length of the source of heat, which correspond to the same dimensional parameters h and l.

Here is indicated: $\xi=\frac{V(z-z')}{2a}$; $X=\frac{V\cdot x}{2a}$; $Y=\frac{V\cdot y}{2a}$; $Z=\frac{V\cdot z}{2a}$; $L=\frac{V\cdot l}{2a}$; $H=\frac{V\cdot h}{2a}$, and $-h<z<h$, $-l<y<l$ (Fig. 2, *a*). In formula (1) the following notation for the Gauss error function (special function) is used $\Phi(s)=\mathrm{erf}(s)=\frac{2}{\sqrt{\pi}}\int_0^s \exp\left(-\xi^2\right)d\xi$.

The purpose of the work is to investigate the continuity of the solutions of three- and two-dimensional differential heat equations to establish the criteria for continuity and the ranges of their changes for the profile grinding conditions. The solution (1) is investigated by comparing it with the solution for a two-dimensional temperature field from a moving strip source (Fig. 2, *b*), which is infinite in the direction of the axis $0y$ ($-\infty < y < \infty$) and having the form in the adopted notation

$$T(Z,X,H)=\frac{2qa}{\pi\lambda V}\int_{Z-H}^{Z+H}\exp(-\xi)K_0\left(\sqrt{X^2+\xi^2}\right)d\xi, \quad (2)$$

where $K_0(s)$ is the zeroth order modified Bessel function of the second kind.

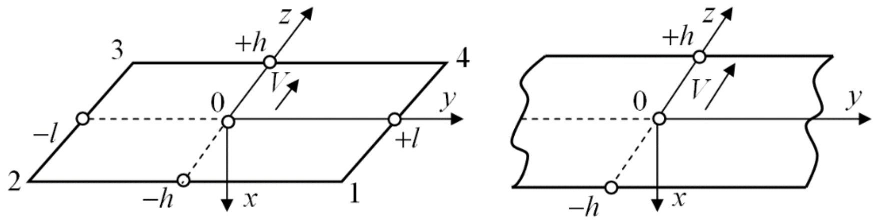

Fig. 2. Rectangular moving heat source (*a*) and a strip one (*b*)

Dividing both parts of equations (1) and (2) into a multiplier $2qa/\pi\lambda V$, we obtain these three- and two-dimensional equations in dimensionless form, respectively:

$$\Theta(X,Y,Z,L,H)=$$
$$=\sqrt{\frac{\pi}{32}}\int_0^\infty \exp\left(\frac{-X^2}{2u}\right)\left(\Phi\left(\frac{Y+L}{\sqrt{2u}}\right)-\Phi\left(\frac{Y-L}{\sqrt{2u}}\right)\right)\times\times\left(\left(\Phi\left(\frac{Z+H+u}{\sqrt{2u}}\right)-\Phi\left(\frac{Z-H+u}{\sqrt{2u}}\right)\right)\right)\frac{1}{\sqrt{u}}du, \quad (3)$$

$$\Theta(Z,X,H)=\int_{Z-H}^{Z+H}\exp(-\xi)K_0\left(\sqrt{X^2+\xi^2}\right)d\xi. \quad (4)$$

As an example, we will calculate the temperature on the surface by the equation (3) multiplied by $2qa/\pi\lambda V$ with the following output data: q = 22.7 · 10^6 W / m^2; a = 5.683 · 10^{-6} m^2 / s; λ = 24 W / (m·° C); V = 0.2 m / s (12 m / min); z = 0; h = 2.72 · 10^{-2} m ($h=\sqrt{Dt_v}/2$; D is diameter of the grinding wheel, D = 0.4 m; vertical grinding depth t_v = 0.074 · 10^{-3} m); l = 3,469 ·10^{-3} m; $Z=-5H...5H$, and X = 0; H = 47.869; L = 17,597. The coordinates along the y axis are the following: y = 0, i.e. Y = 0; $y=l/2$, i.e. Y = 8,799; $y=3l/4$, i.e. Y = 13,198; $y=7l/8$, i.e. Y = 15.397; $y=l$, i.e. Y = 17,597. It is established the maximum temperatures are located practically at the rear edge of the source at $Z=-0,95H$.

Thus, a study of the temperature field in grinding is performed on the basis of the used phenomenological approach to the determination of temperature from the moving flat source in the form of three-dimensional rectangular, two-dimensional strip or one-dimensional that bounded on one side. It is shown that the involute profile curvature cannot be taken into account. It is found areas of the contact zone between grinding wheel and workpiece in which the results of the temperature determination differ by no more than 10%.

The temperature field simulation by means of COMSOL Multiphysics environment is performed. It is established that the maximum values of both the temperature and the heat flow density are located in the involute tooth profile upper part and are in different places of height of tooth, besides the temperature maximum is located below the heat flux density maximum which is located at the top of the tooth. The transient process of formation of the temperature field around the moving thermal source is studied and the thermal saturation time is set. The possibility of replacing the moving (3D) source with the unmoving one (2D) at $H\geq 4$ and $H/L\leq 1$ ($H/L=$ 0.85) is confirmed, since the maximum surface temperatures are close to each other (the difference between them does not exceed 0.7 – 4.03%) in the interval of the heat source velocity (axial feed) from 1m / min to 12m / min. It is established that the greatest influence of cooling on the maximum surface temperature leads to its decrease by 7%. The simulation model confirmed the possibility of replacing the heat source's velocity in a three- and two-dimensional solution with the time of its action in a one-dimensional solution (1D), and also allowed to determine the number of 3 sections in the contact area of the involute surface located at the height of the tooth.

It is established that the optimal number of 3 sections from the possible variants 1, 2, 3, 6 and 9 with heat flux densities, which are averaged over these areas by their instantaneous values. That is, one-dimensional solution can be used in the center of these 3 sections to calculate the temperature.

It is substantiated the use of a solution of a one-dimensional differential heat equation for gear grinding designing and diagnosis, including taking into account the cooling effect of lubricoolant. On the basis of this solution, a single mathematical model of a grinding temperature cycle is developed for heating and forced cooling stages under boundary conditions of the second and third kinds, respectively. The influence of lubricoolant on the grinding temperature and its distribution by the surface layer depth is investigated taking into account the constant and variable temperature of the lubricoolant.

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