DISTRIBUTION OF HEAT FLUX INTENSITY AND TEMPERATURE ON CONTACT SURFACES OF MOVING BODIES (AS APPLIED TO CUTTING OF METALS)

A. N. Reznikov and V. V. Basov

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Using as an example the solution of a problem involving a search for the laws of distribution of heat flux and temperature on the surfaces of cutting tools, a general method is proposed for calculating the intensity of heat flux and temperatures on the contact surfaces of moving bodies.

The analytical solution of the heat balance between two moving bodies has been examined by Jaeger (4). In deriving the formulas, however, he made a number of assumptions which are valid only for preliminary calculations. In particular, he assumed a uniform heat flux distribution for each of the bodies in contact at the contact surface.

In the present paper, on the basis of a combination of analytical calculations and the electrical analog of temperature fields, a method is examined of determining heat flux intensity and temperature between bodies in contact. The method is described in terms of an example in which a search is made for laws of heat flux intensity and temperature distributions on the contact surfaces of cutting tools.

This search is a fairly difficult problem. The cutting process involves bodies of complex shape (the work, the tool, and the chip), and a large number of factors influence the distribution of heat between them. An experimental method has not been found, as yet, for the study of flux intensity distribution in cutting. Meanwhile the search for this law and for the related law of temperature distribution at contact surfaces is a real necessity in the analysis of the physical process of cutting, tool wear, and thermal deformation.

In (1–3), dealing with the thermophysics of the cutting process, the usual assumption is made that the intensity of heat transmission to the tool face from the heated chip, q_f, and the heat transmitted in turn from the tool face to the work, q_b, may be regarded as being uniformly distributed over the whole length of each of the areas in contact (Fig. 1, a). This does not occur in the actual cutting process, however, since the various parts of the contact zone are not heated identically, due to non-uniformity of frictioal forces and different conditions of heat removal. Therefore, the heat fluxes across the contact areas do not remain uniformly distributed. The basis of the method of calculation examined is the assumed equality of temperatures for both pairs (tool-chip and tool-work), respectively, at each point of contact, i.e., it is assumed that there are no temperature discontinuities at the boundaries of the bodies in contact.

To determine the heat flux intensities q_f and q_b, we proceed as follows. We first calculate the chip temperature (1), expressing it in terms of the desired heat flux q_f:

$$\Theta_f(x) = A(x) - B(x)\, q_f(x). \qquad (1)$$

In a similar fashion we also find the temperature

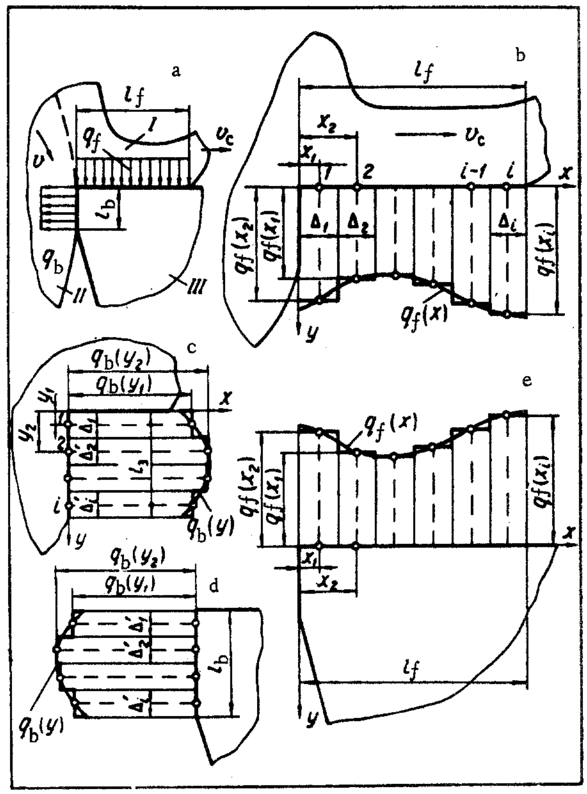

Fig. 1. Method of calculation to determine temperatures and heat fluxes on the contact surfaces of the blade (I—chip, II—work, III—tool): a) diagram of the cutting process; b) heat transmission from the chip to the tool; c) heat transmission from the tool to the work; d) heat fluxes at the back surface of the tool; e) heat fluxes at the front surface of the tool.

$\Theta_b(y)$ on the surface of the work in contact with the tool face:

$$\Theta_b(y) = C(y) - D(y)\, q_b(y). \qquad (2)$$

All the quantities entering into (1) and (2), with the exception of the heat fluxes (sinks) $q_f(x)$ and $q_b(y)$, may be found comparatively easily (1). The question of determining the fluxes $q_f(x)$ and $q_b(y)$ is considerably more complex.

We shall assume that the flux intensities $q_f(x)$ and $q_b(y)$ are known and that their laws of variation are as shown by the solid lines in Figs. 1b and c. We approximate to the functions $q_f(x)$ and $q_b(y)$ by their mean

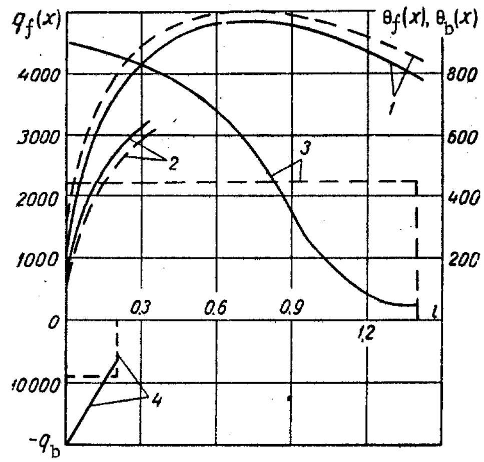

Fig. 2. Heat fluxes and temperatures at the contact surfaces of a sharp tool when turning 1Kh18N9 T steel ($v = 30$ m/min, $S_0 = 0.44$ mm/rev, tool width $B = 4.25$ mm, tool material—hard alloy VK8, $l_f/l_b = 7$): 1) $\Theta_f(x)$; 2) $\Theta_b(y)$; 3) $q_f(x)$; 4) $q_b(y)$.

value in a certain interval. For this purpose we divide the line of contact l_f (Fig. 1a) into sections of width Δ, and the line l_b into sections of width Δ'. We shall

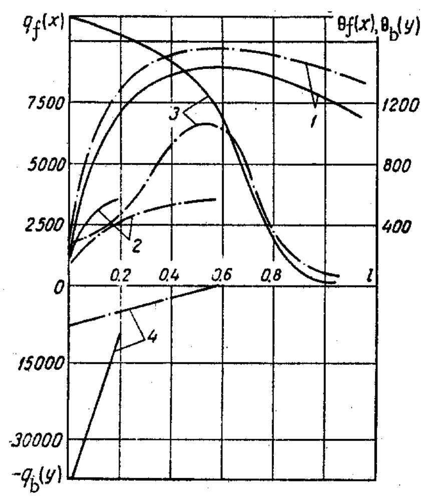

Fig. 3. Heat fluxes and temperatures at the contact surfaces of a sharp $l_f/l_b = 5.5$—solid line) and a blunt ($l_f/l_b = 1.8$—dot-dash line) tool (material being worked 1Kh18N9T steel, $v = 95$ m/min, $S_0 = 0.44$ mm/rev, tool material VK8): 1–4) as for Fig. 2.

assume that the flux intensity remains constant within each section. Then the quantities $q_f(x_1)$, $q_f(x_2)$, ..., $q_f(x_i)$ and $q_b(y_1)$, $q_b(y_2)$, ..., $q_b(y_i)$ (Figs. 1b and c) are the mean values of functions $q_f(x)$ and $q_b(y)$, respectively, in the lengths Δ_1, Δ_2, ..., Δ_i and Δ_1', Δ_2', ..., Δ_i'. It may be seen from Figs. 1b and c that the lowering of temperature of the cut side of the chip due to heat exchange with the tool may be represented as the result of the action of a number of plane sources (sinks) of heat $q_f(x_1)$, $q_f(x_2)$, ..., $q_f(x_i)$, moving in a direction opposite to the descent of the chip with velocity v. On the surface of the work there are sources (sinks) $q_b(y_1)$, $q_b(y_2)$, ..., $q_b(y_i)$, moving in a direction opposite to that of the rotation of the work, with velocity v.

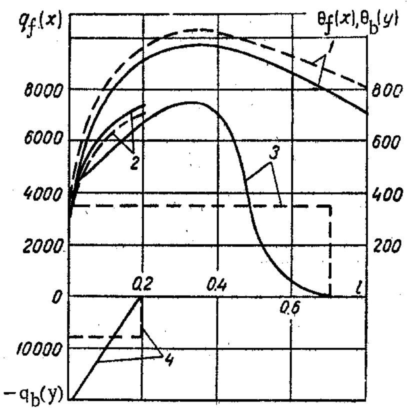

Fig. 4. Heat fluxes and temperatures at the contact surfaces of a worn tool when machining VT-2 ($v = 40$ m/min, $S_0 = 0.14$ mm/rev, tool width $B = 4.25$ mm, $l_f/l_b = 3.55$, tool material VK8): 1–4) as in Fig. 2.

In practice fairly high cutting rates are usually employed, and therefore the formulas for fast-moving sources are used to calculate the temperatures on the contact surfaces of the tool. It is known from the theory of fast-moving sources that practically no heat is propagated ahead of the source (1). Consequently, only the source (sink) $q_f(x_1)$ has an influence on the lowering of temperature of the cut side of the chip at the point 1 (coordinate x_1 in Fig. 1 b). Applying the general formula (1) to calculate the temperature at the point x_1, we obtain:

$$\Theta_f(x_1) = A(x_1) - B_{11}(x_1)\, q_f(x_1). \tag{3}$$

Only the sinks $q_f(x_1)$ and $q_f(x_2)$ affect the temperature at the point x_2:

$$\Theta_f(x_2) = A(x_2) - [B_{21}(x_2)\, q_f(x_1) + B_{22}(x_2)\, q_f(x_2)]. \tag{4}$$

By similar reasoning, we find the temperature at the i-th point on the cut side of the chip:

$$\Theta_f(x_i) = A(x_i) - \sum_{k=1}^{k=i} B_{ik}(x_i)\, q_f(x_k), \tag{5}$$

where k = 1, 2, 3...
The temperature at the i-th point on the surface of the work is found from the formula

$$\Theta_b(y_i) = C(y_i) - \sum_{k=1}^{k=i} D_{ik}(y_i)\, q_b(y_k). \qquad (6)$$

We proceed further as follows. We consider that the temperature is determined by $\Theta_f(x)$ and $\Theta_b(y)$, if we calculate it along the sides of the tool and express it relative to the unknown (desired) fluxes $q_f(x)$ and $q_b(y)$. Relative to the tool, the fluxes $q_f(x)$ and $q_b(y)$ are constant plane heat sources (Figs. 1d and e). Using the principle of superposition, we find the complex temperature field generated in the blade as a result of the action of sources $q_f(x_1)$, $q_f(x_2)$, ..., $q_f(x_i)$ and $q_b(y_1)$, $q_b(y_2)$, ..., $q_b(y_i)$. For this we require data on the temperature field from each of the above-mentioned sources, located at its respective distance from the cutting edge.

Various methods are known of determining temperature fields in cutting wedges, when plane heat sources (1–3) act on the surfaces of the wedge. We used the electrical analog method (3) to solve our problem. The temperature at any point of the wedge from heating by one source is calculated (3) from the electrical analog results by the formula

$$\Theta(x, y) = \frac{ql}{\lambda L} \varkappa(x, y). \qquad (7)$$

If we apply formula (7) to calculate the temperature at the i-th point on the front surface of the tool, due to a number of sources on the front and back surfaces, we obtain

$$\Theta_f(x_i) = \frac{1}{\lambda}\left[\sum_{k=1}^{k=m} \frac{qf(x_k)\Delta_k}{L_{fk}} \varkappa_{fs}(x_{ik}) + \sum_{k=1}^{k=p} \frac{q_b(y_k)\Delta_k'}{L_{bk}} \varkappa_{bd}(y_{ik})\right] \qquad (8)$$

$$(k = 1, 2, 3...).$$

We use (7) to calculate the temperature at the i-th point on the back surface of the tool. As a result we may write

$$\Theta_b(y_i) = \frac{1}{\lambda}\left[\sum_{k=1}^{k=m} \frac{qf(x_k)\Delta_k}{L_{fk}} \varkappa_{fd}(x_{ik}) + \sum_{k=1}^{k=p} \frac{q_b(y_k)\Delta_k'}{L_{bk}} \varkappa_{bs}(y_{ik})\right] \qquad (9)$$

$$(k = 1, 2, 3).$$

We have thus obtained formulas for determining temperatures on the contact surfaces of the tool $\Theta_f(x)$ and $\Theta_b(y)$ on the chip and work side (5), (6) and on the tool side (8), (9). We suppose that at the points x_i and y_i on the contact surfaces the temperatures will be the same, independent of whether the calculation is done from the chip and work side or from the tool side. We therefore equate (5) and (8) and (6) and (9) in pairs, and obtain as a result a system of equations in which the unknowns are the flux intensities at individual points on the contact surfaces of the tool. After solving the system and substituting appropriate values of fluxes in (5) and (8) or (6) and (9), we find the temperature at the front and back surfaces of the tool.

Figures 2–4 show some results of calculating temperatures and fluxes by the above method for various cutting conditions. The solid and dot-dash lines are graphs of $\Theta_f(x)$, $\Theta_b(y)$, $q_f(x)$ and $q_b(y)$, constructed for a flux intensity variation in the cutting zone $q_f(x)$ = = var and $q_b(y)$ = var. The dotted lines are graphs of $\Theta_f(x)$, $\Theta_b(y)$, $q_f(x)$ and $q_b(y)$, constructed on the assumption that $q_f(x)$ = const and $q_b(y)$ = const. Analysis of the graphs of Figs. 2–4 leads to the conclusion that the nature of the flux variation does not remain unchanged, but depends on the particular conditions of cutting and blunting of the tool. As a rule, when working with sharp tools, the maximum value of heat flux, $q_f(x)$ is located at the cutting edge. With increase in the size of the area of wear along the back edge, the maximum intensity of $q_f(x)$ shifts from the edge to the body of the tool (Fig. 3). The heat flux at the rear surface, $q_b(y)$, is negative as a rule, i.e., directed from the tool to the work. The maximum value of the flux intensity $q_b(y)$ is located at the cutting edge, independently of the blunting of the tool. We note the over-all shape of the laws of flux distribution depends on the ratio l_f/l_b.
The higher this ratio is, the closer is the maximum of the curve to the edge.

The rate of cutting has a great influence on the value of the intensity and on the nature of the distribution of fluxes $q_f(x)$ and $q_b(y)$. Increase of the cutting rate (Figs. 2 and 3) from v = 30 to 95 m/min when machining IKhK8N9T steel led to an increase in the flux intensity $q_f(x)$ by a factor of 2.5, and in the flux intensity $q_b(y)$ by a factor of 2.

The flux intensity on the contact areas has a great influence on the temperature $\Theta_f(x)$ and $\Theta_b(y)$. The larger the heat transmission $q_f(x)$ from the heated chip to the tool, the lower the temperature on the front surface. The reduction of the thermal stress of the process on the front surface of the tool is reflected favorably in the wear and stability of tools.

In practice we can artificially create conditions in which the flux intensity into the tool is increased (1) (cooling of the tool, development of lightly loaded edges, etc.).

It is of interest to assess the error of the analytical calculated temperatures on the contact surfaces of the tools, if we suppose that the heat fluxes are distributed uniformly over the whole area in contact.

It may be seen from Figs. 2–4 that the assumption of uniform heat flux leads to increased calculated temperature on the front surface, by 8–12%. The temperature on the back surface proves to be somewhat reduced (on average by 5–10%). At an increased cutting rate these errors prove to be still more considerable, which may give an incorrect picture of the progress of the heat-exchange process.

We have used the above method to determine the laws of heat flux intensity and temperature distributions in the cutting of materials. It may also be applied with success to the analysis of laws of flux and temperature distribution on the contact area of any bodies rubbing, or of systems of bodies located in contact.

NOTATION

A(x), B(x), C(y), D(y)) quantities depending on the location of the points being examined on the front or rear surfaces of the tool; $B_{11}(x)$) a coefficient depending on the location of the point x_1 relative to the source (sink) $q_f(x_1)$; $B_{21}(x_2)$ and $B_{22}(x_2)$) coefficients depending on the location of point x_2 relative to fluxes $q_f(x_1)$ and $q_f(x_2)$; q) heat flux intensity; l) source length; λ) thermal conductivity of the tool material; L) model shape coefficient; L_{fp} and L_{bk}) model shape coefficients for sources on the front and back surfaces; p and m) number of sources on the front and back surfaces, respectively; $\varkappa(x, y)$) dimensionless quantity indicating what proportion of the maximum temperature is the temperature at the point on the wedge with coordinates x, y; $\varkappa_{fs}(x_k)$, $\varkappa_{bd}(y_k)$) quantities similar to $\varkappa(x, y)$. Subscripts: s) indicates that the point examined lies on the same surface as the source; d) on a different surface.

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