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# HEAT-FLOW DISTRIBUTION AND COMBINED HEAT–MASS TRANSFER PROCESSES AT THE CONTACT INTERFACE OF A FRICTION PAIR

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The processes of heat release, heat-flow distribution, and combined heat–mass transfer in sliding contact are analyzed on the basis of measurements of the heat flux directed into one member of a friction pair.

The solution of a number of engineering problems bearing on the need to increase the operational reliability and wear resistance of heavily loaded and high-speed friction components in machines and instruments requires investigation of the laws governing heat exchange (heat-flow distribution) and combined heat–mass transfer at a sliding-contact interface between bodies.

The primary objective here is to determine the working thermal regime of a friction pair (average temperature of the friction surface and the temperature fields relative to frictional contact) as well as to ascertain the causes of wear and the times at which it occurs [1, 2]. Friction thermal problems are solved by the methods of heat-conduction theory under Neumann boundary conditions. As a rule, the specific rate of heat release per unit nominal contact area of the bodies at any instant is known (from measurements of the instantaneous values of F and v) and is given by the equation

$$q = fp_a v.$$

However, to properly account for the heat distribution in frictional contact and, hence, to decide the correct boundary conditions for the solution of friction thermal problems presents considerable difficulty, particularly under the conditions of unsteady heat release, variation of the spacing of the mating friction pair, and combined heat–mass transfer (transfer of heated surface layers from one body to the other). The values of the heat-flow distribution coefficient $\alpha = q_{\alpha_1}/q$ are customarily determined analytically [3]. Expressions for the calculation of α, e.g., in the case of contact between flat bodies are

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derived on the basis of models postulating that the heat sources are flat. Such models do not mirror the true physical picture of the heat-release and heat-exchange processes in sliding contact. Heat generation in the zone of high-speed and heavily loaded sliding contacts takes place in a certain layer (volume). By virtue of the specific nature of friction the heat-generating (plastically overstrained) layer can be a surface layer of one of the friction bodies, while the other body relative to the first can be regarded as absolutely rigid. The transfer of heat from the heat-generating layer into the interior of the friction bodies by heat conduction in this case takes place through different cross sections: in the first body through the minimum contact area, and in the second through the actual contact area. The combined heat—mass transfer process at the contact interface further compounds the difficulty of calculating $\alpha$.

In this article we analyze the results of experimental studies of heat-flow distribution and combined heat—mass transfer in the contact zone of two bodies forming a friction pair, using measurements of the heat flux directed into one of the bodies ("sample"). To simplify the test conditions the experiments were carried out by short-term (transient) braking of a rotating molybdenum disk as a result of friction created by the application of a normal load to a cylindrical sample, whose end face was brought into contact with the cylindrical surface of a disk. The transient nature of the friction process ($Fo_1 < 1$) means that the problem of heat transmission in the sample during braking can be regarded as one-dimensional. The sample was mounted in a textolite mandrel (thermally insulated from the side surfaces and the opposite end), so that heat transfer into the surrounding medium during the friction process could be neglected.

Under the testing conditions described above, the heat flux can be determined by measuring the following in the sample:

a) the temperature gradient in a surface layer of thickness $\Delta_1 = 0.2\text{–}0.3$ mm next to the contact interface;

b) the temperature field $\vartheta_1(z_1, t)$.

The most valuable information about the thermophysical processes in the frictional contact zone is afforded by the results of measurements of the temperature gradient. If the sample has small transverse dimensions, it suffices to measure the temperature at one point on the friction surface ($z_1 = 0$) as well as in the cross sections $z_1 = \Delta_1' \approx 0.2$ mm and $z_1 = \Delta_1'' \approx 0.3$ mm. To monitor the readings of the surface thermocouples and thereby enhance the reliability of the temperature gradient measurements it is advisable to measure the temperature in the cross section $z_1 = \Delta_2 \approx 1$ mm.

The instantaneous value of the temperature gradient is determined from the relation

$$\frac{\partial \vartheta_1}{\partial z_1} = \frac{\vartheta_1(0,\ t) - \vartheta_1(\Delta_1,\ t)}{\Delta_1}.$$

According to the Fourier law of heat conduction,

$$q_{a_1}(0,\ t) = -\lambda_1 \frac{\partial \vartheta_1}{\partial z_1} = -\frac{\lambda_1 [\vartheta_1(0,\ t) - \vartheta_1(\Delta_1,\ t)]}{\Delta_1}.$$

It is essential to note that to measure the heat flux $q_{a_1}(0, t)$ by recording the temperatures $\vartheta_1(0, t)$ and $\vartheta_1(\Delta_1, t)$ under the conditions of transient friction processes presents certain difficulties, requiring appropriate refinement of the testing procedure [4]. It is recommended that the temperature of the friction surface be measured with a composite (consumable) thermocouple, and the temperature at a depth $\Delta_1$ ($\Delta_2$) with a fast-response intrinsic thermocouple [5, 6]. If large wear is observed in the experiment, an additional thermocouple should be placed between those in the cross sections $z_1 = \Delta_1$ and $z_1 = \Delta_2$, at a distance of 0.5-0.6 mm from the end face.

In measuring the temperature field in the sample it is necessary also to record the temperature in cross sections $z_1 \approx b_1/2$ and $z_1 \approx b_1$.

Particular care must be given to the metrological support of the measurements of the transient temperature fields in the sample. The use of intrinsic thermocouples injects the possibility of large systematic measurement errors associated with the transient responses of processes in the system measured variable + measuring device. After placement of the

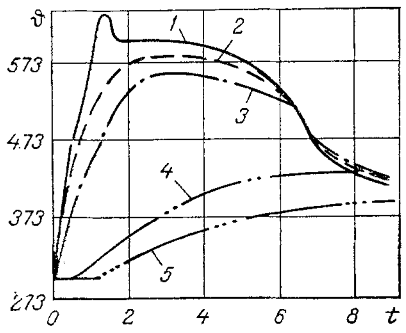

Fig. 1

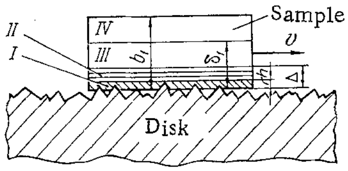

Fig. 2

Fig. 1. Measurement results: temperature $\vartheta$, °K, vs time t, sec, at various heights on a cylindrical sample during the braking process. 1) $\vartheta_1(0, t)$; 2) $\vartheta_1(\Delta_1, t)$; 3) $\vartheta_1(\Delta_2, t)$; 4) $\vartheta_1\left(\frac{b_1}{2}, t\right)$; 5) $\vartheta_1(b_1, t)$.

Fig. 2. Schematic representation of interaction between a sample and a rough disk at the initial instant of braking.

thermocouples in the sample it is necessary to estimate the error of the temperature measurements for each thermocouple and, if the measurement error for a particular thermocouple exceeds a prescribed amount, to relocate it. The metrological support of the transient temperature measurements in the sample provides for the experimental determination of the instrument error, the dynamic characteristic of the thermocouples, and the transient response of the system measured temperature + oscilloscope.

The instantaneous value of the heat stored up by a sample having a constant cross-sectional area $S_{a_1}$ can be determined from the expression

$$Q_{\mathrm{st}_1}(t) = c_1\rho_1 S_{a_1} \int_0^{b_1} \vartheta_1(z_1, t)\, dz_1. \tag{1}$$

Dividing the left- and right-hand sides of (1) by $S_{a_1}t$, we obtain

$$q_{1\mathrm{av}}(0, t) = \frac{c_1\rho_1 \int_0^{b_1} \vartheta_1(z_1, t)\, dz_1}{t}.$$

The values of $q_{a_1}(0, t)$ and $q_{1\mathrm{av}}(0, t)$ for one given time t can differ appreciably from one another. In fact, the values of $q_{a_1}(0, t)$ characterize the singular behavior of the thermophysical processes in the frictional contact zone and, depending on the friction conditions, in certain time intervals they can be equal to zero or even become negative. The values of $q_{1\mathrm{av}}(0, t)$, on the other hand, cannot be negative, because $Q_{\mathrm{st}_1} \geqslant 0$.

For processing of the experimental data the integral $\int_0^{b_1} \vartheta_1(z_1, t)\, dz_1$ was computed graphically.

An Example. The results of temperature measurements in a titanium sample of diameter d = 10.5 mm and height 9 mm are shown in Fig. 1. The temperatures were measured in the cross sections $z_1 = 0$, $z_1 = \Delta_1 = 0.28$ mm, $z_1 = \Delta_2 = 0.88$ mm, $z_1 = b_1/2 = 4.5$ mm, and $z_1 = b_1 = 9$ mm by means of copper–Constantan thermocouples with thermoelectrodes 0.1 mm in diameter. The temperature of the friction surface was recorded with a composite (consumable) thermocouple. The hot junctions of the intrinsic thermocouples were placed in slots with a width of 0.15 mm and depths to 1 mm in the side surface of the sample, which were filled with epoxy-impregnated titanium powder. The metrological support of the measurements ensured that the sum of the systematic and random errors of the temperature measurements in a particular cross section of the sample would not exceed 10%.

TABLE 1. Analytical Data

| $t$, sec | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9,25 |
|---|---|---|---|---|---|---|---|---|---|---|
| $Fo_1$ | 0 | 0,076 | 0,153 | 0,230 | 0,306 | 0,383 | 0,460 | 0,536 | 0,612 | 0,708 |
| $v$, m/sec | 7,5 | 6,69 | 5,88 | 5,07 | 4,26 | 3,45 | 2,64 | 1,83 | 1,02 | 0 |
| $\vartheta_1(0, t) - \vartheta_1(\Delta_1, t)$, K | 0 | 60 | 32 | 20 | 16 | 15 | 2 | 0 | —2 | 0 |
| $\vartheta_1(0, t) - \vartheta_1(\Delta_2, t)$, K | 0 | 105 | 62 | 45 | 36 | 35 | 4 | —8 | —10 | —2 |
| $Q_{st\,1}(t)$, J | 0 | 180 | 339 | 390 | 406 | 410 | 412 | 410 | 408 | 407 |
| $\frac{\partial\vartheta_1}{\partial z_1} \cdot 10^{-3}$, K/m | 0 | 214 | 123 | 77 | 62 | 54 | 71 | —9,5 | —12 | —24 |
| $q(0, t)$, MW/m$^2$ | 7,11 | 6,33 | 5,57 | 4,81 | 4,03 | 3,27 | 2,50 | 1,73 | 0,97 | 0 |
| $q_{av}(0, t)$, MW/m$^2$ | 0 | 6,70 | 6,33 | 5,96 | 5,57 | 5,19 | 4,81 | 4,41 | 4,03 | 3,55 |
| $q_{a_1}(0, t)$, MW/m$^2$ | 0 | 3,44 | 1,98 | 1,24 | 1,00 | 0,95 | 0,11 | —0,15 | —0,19 | 0 |
| $q_{1av}(0, t)$, MW/m$^2$ | 0 | 2,07 | 1,96 | 1,49 | 1,17 | 0,93 | 0,77 | 0,66 | 0,56 | 0,49 |
| $\alpha$ | 0 | 0,54 | 0,35 | 0,25 | 0,24 | 0,29 | 0,04 | —0,08 | —0,19 | — |
| $\alpha_{av}$ | 0 | 0,31 | 0,31 | 0,25 | 0,21 | 0,18 | 0,16 | 0,15 | 0,14 | 0,14 |

During braking the friction force decreased slightly from F = 86 N to F = 78 N ($F_{av}$ = 82 N). The principal data include the initial speed of the disk $v_0$ = 7.5 m/sec, $p_\alpha$ = 1.85 MPa, $t_b$ = 9.25 sec, $\lambda_1$ = 16.1 W/m·K, $c_1$ = 582 J/kg·K, and $\rho_1$ = 4500 kg/m$^3$.

The results of processing of the experimental data are summarized in Table 1. An analysis shows that in the first instants of contact (t = 0-1.375 sec) intense overstraining of the surface layers of the titanium sample causes the average temperature of the friction surface to increase abruptly to 633°K. A heat-generation model applicable to the given situation is shown in Fig. 2. The rough surface of the molybdenum disk is assumed to be absolutely rigid relative to the heated surface layers of the titanium sample. Four zones are observed along the height of the sample. Layer I of thickness h, corresponding to the absolute value of the spacing of the contact surface, receives the normal load. An actual contact area $S_{r_1}$ is formed in this layer. Zone II of thickness $\Delta$ corresponds to the depth of the plastically deformed surface layer. In this zone heat-generation processes occur which are associated with energy spent in overstraining of the surface layers of the sliding element and in overcoming the forces of molecular interaction in the contact zone. Zone III of thickness $\delta_1$ represents the effective zone involved in heat absorption. Zone IV of thickness $b_1 - \delta_1$ is characterized by a temperature close to the initial value $\vartheta_0$.

The heat-generating layer in the given situation is the surface layer of thickness $\Delta$ of the sliding element. Heat is transmitted into the sample by heat conduction from the titanium across the nominal contact area $S_{\alpha_1}$. Heat transfer into the disk, on the other hand, takes place by heat conduction from the molybdenum through the actual contact spot, which has a total area $S_{r_1}$, as well as by heat conduction in the surrounding medium, convective heat transfer, and radiative emission in places where direct contact does not exist between the bodies. Usually, since the voids in the contact zone have finite dimensions, preventing the inception of convective currents, and since radiative heat transfer is slight, we can neglect convective heat transfer and radiative emission [7].

Therefore, inasmuch as the contact is not saturated and the heat source is situated in the surface layers of the sample, the main quantity of heat released in friction is localized in the sample. Consequently, in the time period t = 0-1.37 sec, on the one hand, heat is rapidly stored in a thin surface layer of the sample and, on the other, the boundary layers are eroded in the friction track of the molybdenum disk. The result of these parallel processes is mass transfer of the heated surface layers of the titanium to the disk, diminishing the roughness of the disk and producing a certain saturation of the contact. It is postulated that combined heat—mass transfer takes place mainly in the period t = 1.37-2.00 sec, during which time abrupt decreases are observed in the average temperature of the friction surface, the temperature gradient, and the value of $\alpha$. In this case the surface temperature, temperature gradient, and heat flux into the sample decrease accordingly by the amounts

$$\vartheta_1(0;\ 1{,}37) - \vartheta_1(0;\ 2{,}00) = 633\,^\circ\mathrm{K} - 605\,^\circ\mathrm{K} = 28\,^\circ\mathrm{K},$$

$$\frac{\partial\vartheta_1(0;\ 1.37)}{\partial z_1} - \frac{\partial\vartheta_1(0;\ 2{,}00)}{\partial z_1} = 250\cdot 10^3\ \mathrm{K/m} - 123\cdot 10^3\ \mathrm{K/m} = 127\cdot 10^3\ \mathrm{K/m},$$

$$q_{a_1}(0;\ 1.37) - q_{a_1}(0;\ 2{,}00) = 4.02\ \mathrm{MW/m^2} - 1.98\ \mathrm{MW/m^2} = 2{,}04\ \mathrm{MW/m^2}.$$

The reduction of α during the period t = 2-4 sec evinces a continuing process of combined heat–mass transfer from the sample to the disk, although not as intensely as in the period t = 1.37-2.00 sec.

During the period t = 4-5 sec a repetition of the storing up of heat in the surface layer of the sample is observed (α increases). In the period t = 5-6 sec heat–mass transfer again takes place. From t = 6 sec to the end of the braking operation all the heat released in friction and part of the heat stored in the sample enter the disk. This fact accounts for the variation of the conditions of heat release and heat-flow distribution between the friction bodies. A characteristic model of contact interaction between the sample and the disk for the given case is shown in Fig. 3.

The heat source is the titanium film deposited on the friction track of the molybdenum disk. Contact between the film and the disk is realized across a nominal contact area $S_{a_2}$, and between the film and the sample across the actual contact area $S_{r_1}$. Toward the end of the braking process the sample acquires quite a large quantity of heat, and its average volume temperature approaches the average temperature of the friction surface. Because of the comparatively large mass of the disk, its heat-absorbing capacity is practically unchanged, and the surface layers of the disk can transfer heat into the interior of the disk. On the other hand, toward the end of braking the specific heat-release rate decreases significantly. As a result, the average temperature of the friction surface of the disk becomes lower than the average temperature of the friction surface of the sample, and despite the heat-generation process, heat is transferred from the surface layers of the sample across the area $S_{r_1}$ into the disk by heat conduction.

Figure 4 shows experimental curves of $q_{a_1}(0,\ t)$ and $q_{1\mathrm{av}}(0,\ t)$. The practically identical area under these curves evinces sufficiently high accuracy of measurement of the temperature gradient in the surface layer of the sample.

The investigated situation is representative of the friction conditions in wheel systems, inertial platforms, disk brakes, etc. The heat-generation model shown in Fig. 2 is typical of the frictional contact in high-speed machines and components under "fresh track" friction conditions, where the strength attributes and melting point of the slider are lower than the strength attributes and melting temperature of the rider.

In cases where the sample has large dimensions and the scale factor must therefore be taken into consideration, the temperature gradient and the temperature field must be measured along the normals to several characteristic points of the friction surface.

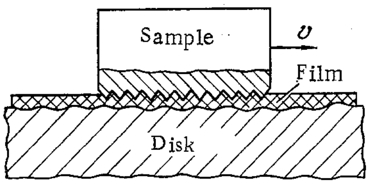

Fig. 3

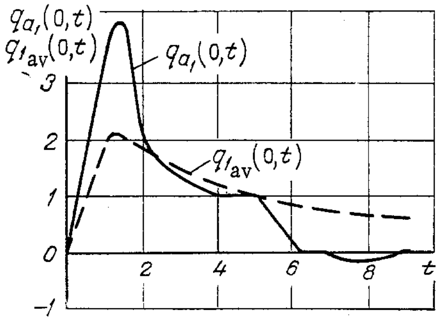

Fig. 4

Fig. 3. Schematic representation of contact interaction between a sample and a disk through a film.

Fig. 4. Experimental heat fluxes $q_{a_1}(0,\ t)$ and $q_{1\mathrm{av}}(0,\ t)$, MW/m², vs braking time t, sec.

## NOTATION

f, coefficient of friction; F, friction force; v, slip velocity; $p_a$, specific load on the nominal contact area; $S_{a_1}$, nominal contact area of the sample; $S_{a_2}$, nominal contact area of the disk; $S_{r_1}$, actual contact area of sample with disk; t, time; $t_b$, total braking time; q, specific rate of heat release per unit nominal contact area; $q_{a_1}$, heat flux into the sample; $\alpha = q_{a_1}/q$, heat-flow distribution coefficient; $q_{1av}$, average heat flux into the sample at a given time; $q_{av}$, average specific rate of heat release per unit nominal contact area at a given time; $\alpha_{av} = q_{1av}/q_{av}$, average heat-flow distribution coefficient at a given time; $Fo_1 = a_1 t/b_1^2$, Fourier number; $b_1$, height of the sample; $a_1$, $\lambda_1$, $c_1$, $\rho_1$, thermal diffusivity, thermal conductivity, specific heat, and density of the sample; $\vartheta_1$, temperature; $\vartheta_0$, initial temperature of the sample; $Q_{st_1}$, quantity of heat stored by the sample at a given time; $z_1$, coordinate along the sample axis; h, spacing of the mating surfaces; $\Delta_1$, $\Delta_2$, coordinates of surface layers; $\delta_1$, thickness of the thermal layer.

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