

MODELING OF TEMPERATURE FLASHES UNDER THE CONDITIONS OF PERIODIC CONTACT OF FRICTION SURFACES

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We propose a generalized mathematical model for determining temperature flashes in the course of sliding of a microasperity along a "discrete-periodic" friction surface. In this model, we take into account the periodic discreteness of friction surfaces and the relation of this feature to their metallophysical structure.

As a result of friction, temperatures, especially in the surface layers of contacting bodies, can reach levels sufficient for structural transformations, tribochemical reactions [1–4], the activation of microcracks initiation or their healing, etc. The combined action of these factors can lead to the fracture of friction surfaces [5–8]. Although all triboeffects manifest themselves in the macroscale, however, the phenomena inducing and accompanying them proceed on the microlevel [9]. For example, temperature flashes arise as a result of the disruption of intermolecular bonds and determine the maximum temperature of joint of microunevennesses on the surfaces of rubbing bodies [10]. Temperature flashes are localized on the actual contact areas, whose size is smaller by two to three orders of magnitude than the apparent contact area [11]. Hence, determining their level experimentally is quite difficult and sometimes even impossible. To simulate temperature flashes, it is necessary to take into account the "multistoreyness" of the geometrical description of a rough surface, which is based on the modern physical and structural concepts of the surface of solids [12, 13]. Temperature flashes arise on two levels of the inhomogeneity of friction surfaces, i.e., on the so-called "levels of roughness and subroughness" [12, 14]. It should be emphasized that the roughness of friction surfaces depends substantially on the metallophysical properties and structure of the materials of friction couples. At certain areas of the friction surface, temperatures can reach or even exceed the melting point of the material or its components, which changes significantly the resistance to surface fracture. Therefore, the approaches based on metal physics and materials science and supplemented with the application of postulates of solid-state physics, thermal physics [2, 3], thermodynamics of irreversible processes, etc. are very important in tribology. In addition, it is necessary to take into account the concept of actual contact areas, which formed the basis of the most known friction theories (molecular and adhesive-deformational) and was time and again confirmed in practice [11, 15, 16].

The conditions of initiation and existence of temperature flashes are connected with numerous theories of friction and wear and represent the subject of inquiry in a separate chapter of the heat dynamics of friction [16, 17]. The determination of their level for different conditions and friction couples is considered to be one of the most important problems of tribology [18]. This is explained by the fact that the local temperature of flashes exceeds significantly the integral average temperature of the friction surface and can reach 900°C [19] or even 1065°C [20]. Therefore, the total temperatures of a friction microsurface (flash and integral average temperatures) affect substantially a series of processes in the course of friction. At the same time, an inverse influence takes place [17]. In view of the short duration of temperature flashes (according to different data, from 10^{-6} sec [20, 21] to 10^{-2} sec [20, 22]), the migration of spots of actual contact, and, as follows from certain investiga-

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tions (see, e.g., [19]), different causes of the initiation of temperature flashes, their theoretical study based on the methods of mathematical modeling seems quite timely.

In what follows, we analyze the principal theoretical approaches and the corresponding mathematical models of temperature flashes and, on this basis, construct a generalized model with regard for “the discrete periodicity” of friction surfaces.

Analysis of the Principal Approaches to the Modeling of Temperature Flashes

The modeling of temperature flashes is mainly based on the approaches developed by Chichinadze and his school [16, 17, 21]. In conformity with these approaches, the maximum temperature on the spots of microcontact is equal to the sum of the integral average temperature (which is a result of the heat flow distributed uniformly over the apparent or contour friction surface) and the temperature of flashes, which give the excess temperature as compared with the integral average one [17, 21]. To calculate the level of a temperature flash, it is customary to consider the motion of a microasperity, which is mainly modeled by a semiinfinite rod (although different approaches to its modeling, e.g., by a hemisphere [20], are possible), along a smooth half-space. The smoothness of the half-space is explained by the following assumption [20, 21]: the average sizes of a contact spot, formed by microasperities, are so small that the surface along which it moves can be considered infinitely large. However, as we show in what follows, this hypothesis usually does not correspond to the actual microstructure of friction surfaces. In the model [21], it is also supposed that the microasperity under consideration is formed by the harder element of the tribocouple and slides along the smooth half-space that models the softer element of the friction couple. Here, the microasperity passes a certain distance L up to the moment of its crushing, which is attributable, first of all, to temperature flashes on the surface of its contact with the half-space. As a result of heating to the critical temperature, the microasperity is softened until its hardness becomes equal to the hardness of the coupled body, which is modeled as a half-space [21]. Then the microasperity moves out of contact [17, 21]. However, it is not necessary that the microasperity crush after its hardness has decreased to the hardness of the half-space.

In [21], the case is considered separately where the critical temperature of the microasperity in the course of its sliding along the half-space is not achieved, i.e., the distance $L \rightarrow \infty$. As follows from here, the microasperity will never be destroyed. However, it is clear that this is impossible in practice since, in this case, the microasperity will move out of contact due to fatigue or other destructive causes. We do not consider here the effect of unwearability caused by the selective transfer of components of the materials of coupled bodies with the participation of the medium [22].

When the integral average temperature is higher than the critical one, the inversion of the harder microasperity and softer smooth half-space takes place [21], i.e., the microasperity plays the role of a half-space and vice versa. Obviously, such an approach is not always correct in view of the microstructure of friction surfaces.

It is customary to think that heat flows along a normal to the friction surface. As shown, e.g., in [20], in the case where the microasperity is modeled not by a rod but by a hemisphere, the greatest heat flow is directed perpendicularly to the half-space, and the temperature falls sharply upon moving away from this direction. To find the level of temperature flashes and the distribution of heat flows between the microasperity and half-space, it is customary to write traditional one-dimensional heat conduction equations with boundary conditions of the second kind [21]:

$$\frac{\partial^2 \vartheta_i}{\partial z^2} = \frac{1}{a_i} \frac{\partial \vartheta_i}{\partial t}, \quad \lambda_i \frac{\partial \vartheta_i}{\partial z} \bigg|_{z=0} = \mp q_i (-q_1 \text{ or } q_2), \quad \vartheta_i = 0 \quad \text{if } z \rightarrow \infty \quad (i = 1, 2),$$

where ϑ_1 and ϑ_2 are the temperatures of the microasperity and half-space, respectively, a_i are their thermal diffusivities, λ_i are the thermal conductivities of the microasperity and half-space, q_1 and q_2 are the specific

heat flows directed into the microasperity and half-space, respectively, z is the direction of heat flow, and t is the time. For both problems, zero initial conditions are usually taken.

Having solved these equations, we obtain the following relation for finding the coefficient of distribution of the heat flows:

$$\alpha = \frac{\sqrt{L\lambda_2\rho_2c_2}}{(\sqrt{L\lambda_2\rho_2c_2} + \sqrt{d\lambda_1\rho_1c_1})}, \quad 1 - \alpha = \frac{\sqrt{d\lambda_1\rho_1c_1}}{(\sqrt{L\lambda_2\rho_2c_2} + \sqrt{d\lambda_1\rho_1c_1})} \quad (q_2 = \alpha, \quad q, \quad q_1 = (1 - \alpha)q),$$

where ρ_1 , c_1 and ρ_2 , c_2 are the densities and specific heats of the microasperity and half-space, respectively, and d is the diameter of the contact spot, which can be calculated as [21]

$$d = \left[\frac{8r_1 h_{1m}}{v_1} \right]^{1/2} \left[\frac{p}{HB_2 b_{01}} \right]^{1/2 v_1}.$$

Here, r_1 is the rounding-off radius of the microasperity, h_{1m} is its height, v_1 and b_{01} are parameters of the reference curve, p is the specific load, and HB_2 is the hardness of the half-space. In the literature, one can find different relations for the coefficient of distribution of the heat flows between the rubbing bodies. For example, Charron's formula is similar to the expression presented above (the same relation without parameters L and d); the former works in the case of equality of the Fourier numbers $Fo_1 = Fo_2$ and the empirical coefficients ψ_{v_1} and ψ_{v_2} , in particular, for the microasperity and half-space [21]. Otherwise, the corresponding formula will be more complex: it will contain the Fourier numbers Fo_1 and Fo_2 (and, hence, the time of contact between the rubbing bodies), the empirical coefficients ψ_{v_1} and ψ_{v_2} , the geometrical sizes of the rubbing bodies, and their thermophysical parameters [21]. We see that such a coefficient of distribution of the heat flows is already non-stationary. It is important to set the time variation of the coefficient of distribution of the heat flows [23] because even slight changes in the heat flow for different moments of time can affect significantly the temperature distribution.

The majority of parameters figuring in these relations depend on the temperature and, hence, on the time of contact between the rubbing bodies. Therefore, in most cases, it is expedient to interpret the coefficient of distribution of the heat flows between the bodies as nonstationary.

In Chichinadze's model [21], the desired quantities are the ranges of lifetimes and rubbing paths of a single microasperity, and the temperature of a flash serves only as an intermediate parameter. The heat flow inducing temperature flashes is calculated as $q = HB_2 v \mu$, where μ is the friction factor and v is the slip velocity [21]. The value of heat flow, a part of which is distributed into the microasperity, depends on the hardness of the half-space along which the microasperity slides but not on the pressure, as is customary to take for friction between macrobodies or macrosurfaces [17]: $Q = P v \mu$, where P is the specific load on the apparent contact.

The most important shortcomings of this model [21] are the following: the microasperity and half-space along which it slides are considered without taking into account the structure (microstructure etc.) of friction surfaces; the distance and time of sliding of the microasperity along the half-space are not determined unambiguously; there are no clear criteria of the microasperity moving out of contact. In the main, these shortcomings were removed in the subsequent models of temperature flashes [23–26]. In particular, in the mathematical model based on a differential equation with functional coefficients [25, 26], it is supposed that the microasperity is formed by the hard component of the heterogeneous structure. In this model, the range of temperatures of the microasperity and the critical temperature of its moving out of contact are found [23] with the use of a new mathematical apparatus in tribology [25]. The critical temperature is taken lower by a factor of 2–2.5 than the melting point of the structure that forms the microasperity [23].

However, both models are based on the following assumptions: the half-space along which the microasperity slides is smooth, the size of the latter is small, and the surface along which it slides is infinite [17, 21]. However, the unboundedness of this surface does not imply that it is smooth. The discreteness of contact between the microasperity and half-space is emphasized in numerous literature data [14], based on the fact that friction surfaces become wavy as a result of friction [27].

Gecim and Winer [20] consider the nonstationary temperature distribution near the spots of contact between microunevennesses under friction conditions. It is characteristic that a microunevenness, which is not necessarily identical to a microasperity in Chichinadze's model [21], represents here the subject of inquiry. Correspondingly, the geometrical sizes of the microunevenness are not defined clearly, whereas Chichinadze's model gives relations for finding the diameter of a contact spot formed as a result of contact between the microasperity under consideration and half-space along which it slides. Gecim and Winer approximate the microunevenness by a hemisphere of radius $0 < r \leq r_1$, but not by a rod since the sizes of the former are not defined (it can correspond not only to the level of roughness and subroughness but also to waviness [14]). However, the size of the contact spot itself affects substantially the level of temperature flashes [20]. The length of the contact spot can also be much greater than its height. Hence, the model [20] does not give a clear differentiation "whether the hot spot is formed by collision of asperities on either surface, or by a rather prolonged rubbing of an asperity against the surface" [20]. It should be noted that the idea of the initiation of temperature flashes as a result of collision between microasperities, which afterwards form a single contact spot, served as a basis of another model [19]. Correspondingly, Gecim and Winer's model [20] deals only with a local increase in the temperature but not with temperature flashes. Hence, the heat flow is found in [20] with the use of a relation that is intermediate between the contact of friction macrobodies and the interaction of a microasperity with a half-space in conformity with Chichinadze's model: $q = p_m v \mu$. Here, p_m is the indenter hardness, which is approximately equal to the yield point and can be found as

$$p_m = \frac{W}{A_r},$$

where W is the specific load and A_r is the actual contact area.

However, the most characteristic feature of the model [20] probably consists of the assumption that the physical picture of the thermal behavior of asperities "represents the case of an asperity moving out of contact, and its temperature decaying until the following contact takes place" or "may also represent the intermittent interaction of asperities within an apparent area of contact." Hence, two subproblems are considered in this model: the heating of a microunevenness and its cooling. The first subproblem is described by

$$\frac{\partial^2 T}{\partial r^2} + \frac{1}{r} \frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial Z^2} = \frac{1}{a} \frac{\partial T}{\partial t},$$

$$\lambda \frac{\partial T}{\partial Z} = \begin{cases} -q, & 0 \leq r \leq r_0, \\ 0, & r > r_0, \end{cases} \text{ for } Z = 0; T \rightarrow 0 \text{ for } \sqrt{r^2 + Z^2} \rightarrow \infty; T|_{t=0} = 0,$$

where T is the temperature and r and Z are cylindrical coordinates.

The problem where convective heat transfer takes place on the surface of the hemisphere is considered in [20] separately. For cooling, the problem is given by

$$\frac{\partial^2 u}{\partial \rho^2} + \frac{1}{\rho} \frac{\partial u}{\partial \rho} + \frac{\partial^2 u}{\partial z^2} = \frac{r_0^2}{a} \frac{\partial u}{\partial t}, \quad u(\rho, z, t=0) = \int_0^\infty \frac{J_0(\alpha \rho) J_1(\alpha) \exp(-\alpha z)}{\alpha} d\alpha$$

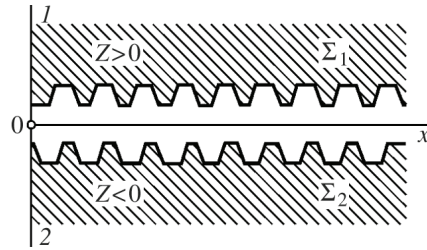


Fig. 1. A model of friction microsurfaces [31]: solids in contact (1 and 2).

(in fact, this is the solution of the preceding problem, i.e., the condition $u|_t = u_0 \neq 0$ is used here), $\frac{\partial u}{\partial z} = Bu$ for $z = 0$, $t > 0$, and $\rho \geq 0$. Here,

$$\rho = \frac{r}{r_0}, \quad z = \frac{Z}{r_0}, \quad u = \frac{\lambda T}{qr_0}, \quad \text{and} \quad B = \frac{hr_0}{\lambda}$$

is the Biot number, where h is the convective heat transfer coefficient and J_0 ($i = 0, 1$) are Bessel functions. Thus, the following two cases are considered in [20]:

- (a) the temperature disturbance in the contact zone decays completely after the given point has moved out of the contact zone even earlier than the next, periodically repeated contact appears;
- (b) the heat of successive collisions of the asperities of microunevennesses is accumulated within the limits of the apparent contact area because the time between collisions is insufficient for cooling.

However, the model [20] does not give a clear answer to the important question: when and why are the microunevennesses destroyed (i.e., move out of contact)? It should be emphasized that, in the first case, their contact would theoretically be able to last infinitely. In the second case, it is also impossible to understand when energy accumulation becomes critical for the existence of the microunevenness under consideration. In addition, it is not known what is the cause of periodicity of contact between the microunevennesses, and how one can associate this phenomenon with the metallographic structure of the surface. An answer to the first question is probably given by the criterion of microasperity moving out of contact with the smooth half-space, which was first accepted in Chichinadze's model [21], and also by another criterion substantiated in the new model of temperature flashes [23].

Regularity of the Relief of a Friction Surface and "Temperature Waves"

In few works devoted to the wave manifestations of the fields of elastic strains induced by friction [28–31], a periodic or quasiperiodic relief, along which an indenter moves, is considered in the main. (Periodicity can be disturbed by inclusions and defects, in particular, by dislocations [12].) Adirovich and Blokhinzev [31] were the first to investigate this phenomenon with the corresponding approach to the modeling of the roughness of surfaces.

Comparing such approaches to the modeling of contact surfaces of the rubbing bodies with Chichinadze's [21] and Gecim and Winer's [20] models, we can see a clear analogy between them. A hard microasperity (in-

denter), moving along a softer half-space, trims the crests of waves on it. This explains the “periodic-discrete” character of the half-space along which the microasperity (or, more exactly, a group of periodically situated microasperities) slides [12, 31]. As a result of changes in the hardness due to heating, the inversion of the half-space and microasperities can occur when, according to Chichinadze [17, 21], the “trimmed” sites themselves begin to play the role of harder microunevennesses, and the plane with microasperities periodically situated on it, owing to their softening, becomes a “periodic-discrete” sliding surface. Hence, in any case, we may speak of peculiar “temperature waves,” attributable to the periodic structure of friction surfaces. In other words, there appear oscillations of thermal energy periodic in time and space.

In the literature, one can find particular approaches to the explanation of the appearance of such regular structures on friction surfaces. For example, according to [32], they arise owing to frictional self-sustained oscillations. As follows from the experimental and theoretical data presented in [11, 14], as a result of friction of even perfectly smooth surfaces under conditions of its stabilization, there arises an equilibrium periodic or quasi-periodic relief on the actual contact areas of microsurfaces of the rubbing bodies. Analysis of the correlation functions of even irregular roughness (but we here consider regular roughness) shows [33] that, among the unevennesses of the profile of a surface, the periodically repeated unevennesses occupy a great part. These and similar literature data are considered in [14].

It is clear that the actual relief of a friction surface is not completely periodic but represents a superposition of the wave harmonics of different lengths (which correspond to different frequencies of the Rayleigh waves), including the inhomogeneities of friction surfaces [12], however, in a certain approximation, one may assume that the actual relief is periodic. Hence, in modeling temperature flashes it is logical to consider a “discrete-periodic” surface along which a microasperity slides. In Chichinadze’s [21] and our [23, 25, 26] models, the geometrical and thermophysical parameters characterizing a microasperity and a half-space are used fairly widely, but the periodicity of location of the unevennesses is not taken into account. Furthermore, the metallophysical aspects of the formation of a periodic structure on friction surfaces are not considered in all the approaches described above.

A Generalized Model of Temperature Flashes

As in the preceding models [20], the microasperities (Fig. 2) are formed by the hard component of microstructure of the friction surface and slide along the discrete-periodic surface of the half-space (i.e., along the periodically situated contact sites and depressions where contact is absent), formed by the softer element of the friction couple. To find the level of temperature flashes, we consider the temperature distribution in a single microasperity, which is modeled by a semiinfinite rod. We suppose that this microasperity slides along a smooth half-space, i.e., one of the periodically situated sites of friction microsurface of the antibody is in contact. As in the preceding models [17, 21, 23], we assume that the microasperity moves out of contact as a result of its crushing at the critical temperature, which is close to a half of the melting point of the component of microstructure that forms this microasperity [23]. Within the limits of a single site, the following cases are possible:

- (i) as a result of a temperature flash, the microasperity is heated to the critical temperature and moves out of contact;
- (ii) the microasperity is heated to a temperature lower than the critical one. Then, within the limits of a “pit,” where contact is absent, the microasperity cools down. We suppose that cooling is incomplete. Hence, the microasperity, passing along several sites within the limits of the actual contact area, accumulates energy and, after several heating–cooling cycles, is heated to the critical temperature and moves out of contact;
- (iii) the temperature flash has a sufficient time in the course of passage of the “pit” zone for complete decay up to the moment of appearance of the next contact.

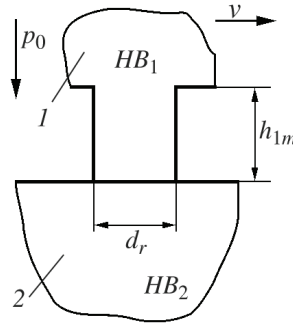


Fig. 2. Friction of a single asperity: microasperity (1) and half-space (2).

In the first case, to find the level of a temperature flash, we can apply directly the mathematical model [23], where the postulates of Chichinadze's model [17, 21] were developed and generalized. Further, in the third case (theoretical "unwearability" of the microasperity), it is possible to apply the mathematical model based on the principles of fatigue fracture mechanics [6]. This case also corresponds to the postulates of Chichinadze's model [21], where the sliding distance of the microasperity $L \rightarrow \infty$, i.e., the critical temperature is not reached on its surface.

Consider the second case. We assume that the temperature of a single microasperity can be found as a sum of the integral average temperature of the surface and the temperature flash [21, 23]. It is clear that both temperatures depend on the parameters of loading of the friction couple and its thermophysical properties, and the temperature of a flash depends also on the microstructure of the friction surface, the thermophysical parameters of its components, hardness, and sizes [21]. Both the integral average temperature of the friction surface and temperature flashes are determined by solving the heat conduction problem with boundary conditions of the second kind [25]. In the general case, these equations and conditions have the form [23, 25]

$$\frac{\partial T(x, t)}{\partial t} = a^2 \frac{\partial^2 T(x, t)}{\partial x^2} + p(x, t)T(x, t) + q_1(x, t) \quad (0 < x, t < \infty), \quad (1)$$

$$T(x, 0) = \varphi(x) \quad (0 \leq x < \infty), \quad (2)$$

$$\left. \frac{\partial T(x, t)}{\partial x} \right|_{x=0} = \psi(t) \quad (0 \leq t < \infty), \quad (3)$$

where $t = T(x, t)$ is the desired temperature (integral average temperature of the surface or that of a flash). Since the sizes of microasperities are fairly small even as compared with the site of sliding, we consider the latter to be infinite and, for the sake of generality, do not bound also the corresponding contact time. We take

$$p(x, t) = -\frac{h(x, t)}{c\rho},$$

where $h(x, t)$ is the convective heat transfer coefficient and $q_1(x, t)$ is the density of additional heat sources. It should be noted that, as established in [23], the influence of convective heat transfer is different in principle for friction macro- and microsurfaces.

We assume that $q_1(x, t) \equiv 0$, although this is not a matter of principle. We assign the function $\psi(t)$ in terms of the heat flow $q(t)$ arising owing to friction on the contact surface, i.e.,

$$\psi(t) = -\frac{\alpha(t)q(t)}{\lambda}.$$

Here, $\alpha(t)$ is the coefficient of distribution of the heat flows between the rubbing bodies, which, together with the value of heat flow $q(t)$, can be found by the well-known relations [16, 20, 21].

The value of heat flow can depend substantially on the decrease in the hardness of microasperity due to its heating, which can be determined as $HB = HB_0 \exp(-kT)$, where HB_0 is the hardness at room temperature, k is an empirical coefficient, and T is the temperature [11]. To remove the nonlinearity of the problem, it is expedient to determine changes in the hardness not directly by the temperature but using its time variation.

We take the function assigning the temperature distribution prior to the beginning of friction as $\varphi(x) \equiv \text{const} = 18^\circ\text{C}$. The solution of system (1)–(3) can be found analytically and written in terms of the Wiener integrals [25]:

$$\begin{aligned} T(x, t) = & x\psi(t) + \int_C \exp \left\{ t \int_0^1 p[|\eta|, \eta_3] d\tau \right\} \{ \varphi[|\eta_1|] - \psi(0)|\eta_1| \} W(dy) \\ & + \int_0^t d\sigma \int_C \exp \left\{ (t - \sigma) \int_0^1 p[|\eta|, \eta_2] d\tau \right\} \{ q_1[|\eta_1|, \sigma] + \psi(\sigma)|\eta|p[|\eta_1|, \sigma] - \psi'(\sigma)|\eta_1| \} W(dy), \end{aligned}$$

where

$$\eta = 2a\sqrt{t - \sigma}y(\tau) + x, \quad \eta_1 = \eta|_{\tau=1}, \quad \eta_2 = (t - \tau)(1 - \tau), \quad \eta_3 = t(1 - \tau),$$

and $W(dy)$ is the Wiener measure. The cooling of a microasperity in the course of its motion past a depression is simulated by

$$\frac{\partial T_1(x, t)}{\partial t} = a^2 \frac{\partial^2 T_1(x, t)}{\partial x^2} + p(x, t)T_1(x, t) \quad (0 < x, t < \infty), \quad (4)$$

$$T_1(x, 0) = T_{n_1} \quad (0 \leq x < \infty); \quad \left. \frac{\partial T_1(x, t)}{\partial x} \right|_{x=0} = 0 \quad (0 \leq t < \infty), \quad (5)$$

where T_{n_1} is the temperature of the microasperity at the moment of completion of the first sliding cycle along the first contact site of a “discrete-regular” surface. In other words, T_{n_1} is the solution of problem (1)–(3), and here $T_{n_1} < T_{\text{cr}}$, where T_{cr} is the critical temperature at which the microasperity moves out of contact. If convective heat transfer takes place only on the apex of the microasperity, the heat flow on the friction surface (more exactly, the heat removal) is determined as a function of the Biot number [20], and then $p(x, t) \equiv 0$.

The analytical solution of problem (4), (5) is given by

$$T_1(x, t) = x\psi(t) + T_{n_1} \int_C \exp \left\{ t \int_0^1 p[|\eta|, \eta_3] d\tau \right\} W(dy) + \int_0^t d\sigma \int_C \exp \left\{ (t - \sigma) \int_0^1 p[|\eta|, \eta_2] d\tau \right\} W(dy).$$

Further, after cooling of the microasperity to a temperature T_c , which is obtained from the solution of system (4), (5), we again consider problem (1)–(3), only taking $\varphi(x) = T_{c1}$. Then we again solve the problem of cooling of the microasperity (4), (5) and take $\varphi(x) = T_{n2}$, where T_{n2} is the temperature of the microasperity at the moment of completion of the second sliding cycle along the second contact site, and so on. This process “heating–cooling–heating” continues until the temperature achieves the critical level (according to our criterion of the microasperity moving out of contact, 0.4–0.5 of its melting point) [23]. Obviously, these considerations are valid only in the case where cooling is incomplete, i.e., heat is accumulated [20]. Then we find the time of existence of the microasperity as the sum of the times of “heating” and “cooling” cycles.

CONCLUSIONS

The duration of “heating–cooling” cycles for a microasperity in the course of friction depends on numerous factors: the length of contact areas and the distances between them; the geometrical sizes of the microasperity and, correspondingly, of the contact spot (i.e., on the microstructure of the friction surface); the microhardnesses of components of the microstructure and their thermophysical characteristics. Our mathematical model takes into account all these parameters and, hence, the metallophysical features of the microstructure of friction surfaces. The time of existence of a microasperity is closely connected with the wear of the friction surface under consideration. The model proposed is applicable not only for contact sites disposed regularly but also in other cases of a “discrete-periodic” friction surface. For computations, it is necessary only to assign a certain law of arrangement of these sites.

The assignment of functions and relations figuring in problems of the type (1)–(3) and (4), (5) and, therefore, their solution requires additional investigations.

Thus, the model constructed in this paper generalizes, combines, and develops the well-known approaches to finding temperature flashes.

REFERENCES

1. G. Heinecke, *Tribochemistry*, Akademie-Verlag, Berlin (1984).
2. B. I. Kostetskii, *Surface Strength of Materials during Friction* [in Russian], Tekhnika, Kiev (1976).
3. I. M. Lyubarskii and L. S. Palatnik, *Metallophysics of Friction* [in Russian], Metallurgiya, Moscow (1976).
4. V. G. Pinchuk and E. G. Shidlovskaya, “Interrelation between microstructural changes and the kinetics of wear of the surface layer of a metal during friction,” *Trenie Iznos*, No. 6, 965–972 (1989).
5. A. E. Andreikiv, V. V. Panasyuk, and M. V. Chernets, “On the theory of wear of materials during dry friction,” *Fiz.-Khim. Mekh. Mater.*, **17**, No. 2, 51–75 (1981).
6. A. E. Andreikiv and M. V. Chernets, *Evaluation of the Contact Interaction of Rubbing Machine Elements* [in Russian], Naukova Dumka, Kiev (1981).
7. O. V. Maksymuk, V. V. Shyrovov, and H. S. Kruk, “Modeling and calculation of the wear of coatings,” in: *Proc. IV Int. Symp. “Triboengineering-2002”* [in Ukrainian], (Ternopil, Sept. 23–27, 2002), Vol. 2, Ternopil (2002), pp. 761–765.
8. V. V. Panasyuk (editor), *Fracture Mechanics and Strength of Materials: Handbook* [in Russian], Vol. 1: V. V. Panasyuk, A. E. Andreikiv, and V. Z. Parton, *Foundations of the Fracture Mechanics of Materials*, Naukova Dumka, Kiev (1988).
9. A. I. Sviridenok, N. K. Myshkin, T. F. Kalmykova, and O. V. Kholodilov, *Acoustic and Electric Methods of Triboengineering* [in Russian], Nauka i Tekhnika, Minsk (1987).
10. H. Blok, “The flash temperature concept,” *Wear*, **6**, 483–494 (1963).
11. I. V. Kragel'skii, M. N. Dobychin, and V. S. Kombalov, *Principles of Friction and Wear Calculations* [in Russian], Mashinostroenie, Moscow (1977).
12. A. I. Sviridenok, S. A. Chizhik, and M. I. Petrokovets, *Mechanics of Discrete Frictional Contact* [in Russian], Nauka i Tekhnika, Minsk (1990).

13. N. B. Demkin, *Contacting of Rough Surfaces* [in Russian], Nauka, Moscow (1970).
14. Yu. I. Koval'chik, "Simulation of wave processes under conditions of friction of rough surfaces (review)," *Fiz.-Khim. Mekh. Mater.*, **39**, No. 4, 101–111 (2003).
15. I. V. Kragel'skii, *Friction and Wear* [in Russian], Mashinostroenie, Moscow (1968).
16. M. Hebda and A. V. Chichinadze (editors), *Handbook on Triboengineering* [in Russian], Vol. 1: *Theoretical Foundations*, Mashinostroenie, Moscow (1989).
17. A. V. Chichinadze (editor), *Principles of Tribology (Friction, Wear, and Lubrication)* [in Russian], Nauka i Tekhnika, Moscow (1995).
18. J. Sadowski and L. Sarnowich, "Energetyczna metoda oceny "temperatury zblysku," *Tribologia*, No. 5, 485–496 (1995).
19. V. A. Likhachev, V. E. Panich, E. É. Zashchuk, et al., *Cooperative Deformation Processes and Localization of Strains* [in Russian], Naukova Dumka, Kiev (1989).
20. B. Gecim and W. O. Winer, "Transient temperatures in the vicinity of an asperity contact," *Trans. ASME, J. Tribol. Technol.*, **107**, No. 3, 333–342 (1985).
21. A. V. Chichinadze, É. D. Braun, A. G. Ginzburg, and Z. V. Ignat'eva, *Calculation, Testing, and Selection of Friction Couples* [in Russian], Nauka, Moscow (1979).
22. D. N. Garkunov (editor), *Enhancement of Wear Resistance Based on Selective Transfer* [in Russian], Mashinostroenie, Moscow (1977).
23. V. V. Shyrokov and Yu. I. Koval'chik, "Simulation of temperature flashes with regard for the physicomaterial properties of metals," *Fiz.-Khim. Mekh. Mater.*, **34**, No. 3, 36–48 (1998).
24. O. V. Pereverzeva and V. A. Balakin, "Heat distribution between rubbing bodies," *Trenie Iznos*, No. 3, 507–517 (1992).
25. Yu. Koval'chik, *Wiener and Feynman Integrals: Calculations and New Possibilities of Application* [in Ukrainian], Vertykal', Lviv (1998).
26. Yu. I. Koval'chik and M. I. Pashechko, "Simulation of temperature fields in a microasperity during friction," *Trenie Iznos*, No. 6, 719–725 (1996).
27. Sh. M. Bilyk, "Formation of transverse periodic unevennesses on the surfaces of solids in the course of friction," in: *Friction and Wear in Machines* [in Russian], Issue 17 (1962), pp. 71–79.
28. S. V. Krysov and A. L. Orlov, "On the interrelation between the wave properties of bodies and the kinetic dependence of friction forces," *Trenie Iznos*, No. 4, 610–616 (1991).
29. S. V. Krysov, *Forced Oscillations and Resonance in Elastic Systems with Moving Loads* [in Russian], Preprint of the Gor'kii State University, Gor'kii (1985).
30. E. V. Zolotareva and A. L. Orlov, "A wave analog of the rod model of a contact," in: *Problems of Friction and Wear* [in Russian], Issue 42, Tekhnika, Kiev (1992), pp. 6–11.
31. T. Adirovich and D. Blokhinzev, "On the forces of dry friction," *J. Phys. USSR*, **7**, No. 1, 29–36 (1943).
32. I. V. Kragel'skii and N. V. Gitis, *Frictional Self-Sustained Oscillations* [in Russian], Nauka, Moscow (1987).
33. Ya. A. Rudzit, *Microgeometry and Contact Interactions of Surfaces* [in Russian], Zinatne, Riga (1975).