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MODELLING OF TEMPERATURE FLASHES IN THE CONDITIONS OF SLIDING OF DISCRETE ROUGH FRICTION SURFACES

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Abstract. A summarized mathematical model for the calculation of temperature flashes under sliding interaction of a microlug on the "discrete and periodic" friction surface is proposed. It takes into consideration the periodic discreetness of friction surface and also its connection with metallophysical structure.

Keywords. Modelling, temperature flashes, friction surface, Wiener integral.

1. INTRODUCTION

As a result of friction in the surface layers of contacting bodies a rise of temperature to the values sufficient for structural transformations, tribochemical reactions and other related processes is possible. Despite the fact that all triboeffects appear on a macroscale level, the phenomena that cause and accompany them are concentrated on a microlevel. Temperature flashes appear as a result of breaking the intermolecular bonds and determine the maximum temperature of irregularities joints on the surface of tribocouples. These are localized on the real contact spots, sizes of which are by 2–3 orders of magnitude less that the nominal ones.

When modeling the temperature flashes, it is necessary to consider the "multistory" of the friction surface roughness, that corresponds to the modern physical and structural notions on the composition of solids. Temperature flashes appear on two levels of friction – levels of "roughness" and "subroughness". Simultaneously metallophysical properties and structure of the material of friction couples significantly affect the surface roughness.

Local temperature as a result of an instant effect of temperature flashes can significantly exceed the average integral temperature and reach 900 °C or even 1065 °C. Therefore, the experimental determination of their values is a complex task. Since the time of temperature flashes existence is very short, varying from 10^{-6} to 10^{-2} s, migration of real contact spots and also different causes of temperature flashes formation, their theoretical study using the methods of mathematical modelling, is a topical scientific problem [1–7].

2. PROBLEM FORMULATION

According to a majority of existing concepts the temperature flashes appear, in particular, during a microlug movement, which is modelled by a semi-infinite rod, sliding over a smooth semi-space simulating a solid. A necessary condition is that a semi-space is smooth and a microlug is small in size, thus enabling consideration of the surface over which it slides as a semi-infinite one. Still, the smoothness of a semi-space does not always correspond to the real microstructure of the friction surface. A microlug is formed by a harder element of the tribocouple and it rubs a semi-space that simulates a less hard counter-body. In many approaches a way L, which a microlug passes to the

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moment of its crushing, and not the value of temperature flashes, is determined first of all (see Fig.1). In this case this crushing takes place due to softening of the microlug with temperature rise until its hardness does not decrease to the level of a softer element of the tribocouple. It should be noted that as a result of the microlug hardness decrease to the hardness of a semi-space the microlug does not obligatory crush.

In case when the average temperature exceeds the critical one, the inversion between a harder microlug and a softer smooth semi-space takes place, that is, a microlug is considered as a semi-space and vice versa. Similar notions are not always correct considering the microstructure of the friction surface. Note also that such approaches do not consider the effect of non-wear, when a way of that a microlug passes tends to infinity.

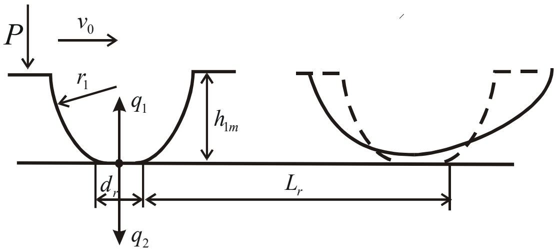

Figure 1. The scheme of sliding of a single microlug over a semispace.

For determining a microlug way L_r, and also the value of temperature flashes a system of ordinary one-dimensional differential equations with the second kind boundary conditions is solved [4],

$$\frac{\partial^2 \vartheta_i}{\partial z^2} = \frac{1}{a_i^2}\frac{\partial \vartheta_i}{\partial t}\,;\;\; \lambda_i \left.\frac{\partial \vartheta_i}{\partial z}\right|_{z=o} = q_i \;\; (-q_1 \text{ or } q_2\,);\;\; \vartheta_i = 0 \text{ at } z \to \infty \;\; (i = 1,2),$$

where ϑ_1 , ϑ_2 are the temperatures of a microlug and a semi-space, a_i λ_i is thermal conductivity for the microlug and a semi-space, q_1 and q_2 are intensity of heat flows directed into a microlug and a semi-space, respectively, z is direction of heat distribution, t is time. Initial conditions are assumed to be zero.

3. ANALYTICAL SOLUTIONS

Coefficient of heat flows distribution that in the model [4] is written as $\alpha = \dfrac{\sqrt{L_r \lambda_2 \rho_2 c_2}}{\sqrt{L_r \lambda_2 \rho_2 c_2} + \sqrt{d_r \lambda_1 \rho_1 c_1}}$,

where ρ_1, c_1 and ρ_2, c_2 are densities and coefficients of thermal conductivity for a microlug and a semi-space, d_r is diameter of a contact spot, is very important in distribution of heat over the friction surface.

However, as a result of the performed analysis it turned out that in such type of setting the coefficient of heat flows distribution the given model is not applicable in the calculations for the most friction couple materials. In modifications of the model to find the distribution of heat flows the correlations of Sharron, Blok and Jeager were used. In this case the maximum value of temperature flashes $\vartheta^*_{1\max}$ was calculated by formulas:

$$\vartheta^*_{1\max} = \frac{2q}{\sqrt{\pi}} \frac{\sqrt{t_r}}{\sqrt{\lambda_1 \rho_1 c_1} + \sqrt{\lambda_2 \rho_2 c_2}} + \vartheta^*_a, \tag{1}$$

$$\vartheta^*_{1\max} = \frac{2q}{\sqrt{\rho_1 c_1}} \frac{\sqrt{\vartheta_0 d_r \lambda_1 t_r}}{\lambda_1 \sqrt{\pi \upsilon_0 d_r} + 4\lambda_2 \sqrt{a_1}} + \vartheta^*_a, \tag{2}$$

$$\vartheta^*_{1\max} = \frac{14q}{\sqrt{\pi}\rho_1 c_1} \frac{\lambda_1 \sqrt{t_r}}{7\lambda_1 \sqrt{a_1} + 4\lambda_2 \sqrt{d_r \upsilon_0}} + \vartheta^*_a, \tag{3}$$

where ϑ^*_a is initial temperature of a body, υ_0 is sliding rate of a microlug.

Formulas for calculation of the coefficient of heat flows distribution between the microlug and a semi-space are rather approximate. First of all, this is related with very small sizes of the microlug, changes of the form and sizes of the contact spot, short time of the interaction. Therefore, there is a large scattering of temperature values in the contact spot region, specifically for the relatively great sliding rates. As a result the experimental data on the temperature distribution can differ significantly for the concrete couples of friction show that with the increase of the rounding of a microlug radius r_1, and thus the diameter of the contact spot, the values of the coefficient of heat flows distribution, calculated by the formulas of different authors, converge (Fig.2).

The value of the heat flow is found from formula $q = HB_2 \upsilon_0 \mu$, where HB_2 is a semi-space hardness, μ is friction coefficient.

In the model of B. Jessim, W. Wiener no temperature flashes are meant but only local increase of temperature for a microlug, which sizes are not clearly defined. In this case a heat flow is found from the formula $q = p_m \upsilon_0 \mu$, where p_m is indenter hardness approximately equal to the yield strength and which value is found from correlation $p_m = W / A_r$, where W is specific loading, A_r is actual contact area.

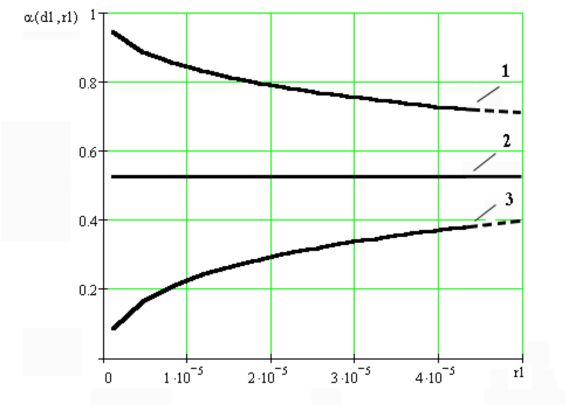

Figure 2. The change of heat distribution coefficient versus radius of the microlug rounding according to formula: 1 – by Jaeger; 2 – by Sharron; 3 – by Block.

Another significant drawback of the model of temperature of temperature flashes and its modifications is neglecting of the effect of hear release on temperature, especially in the conditions of lubricating friction. Besides, a criterion of reaching the critical temperature is determined unclearly. From this follows an incorrect determination of the way and time of a microlug sliding.

Model has no such drawbacks. It is constructed on the base of the equation of heat conductivity with functional coefficients and the second kind boundary conditions.

$$\frac{\partial T(x,t)}{\partial t} = a^2 \frac{\partial^2 T(x,t)}{\partial x^2} + p(x,t)T(x,t) + q_1(x,t) \qquad (0 < x, t < \infty); \qquad (4)$$

$$T(x,0) = \varphi(x) \qquad (0 \le x < \infty); \qquad (5)$$

$$\left. \frac{\partial T(x,t)}{\partial x} \right|_{x=0} = \psi(t) \qquad (0 \le t < \infty), \qquad (6)$$

Where $T=T(x,t)$ is temperature of the flash; $p(x,t) = -\dfrac{h(x,t)}{c\rho}$, $h(x,t)$ is coefficient of convective heat exchange. Using $q_1(x,t)$ a density of the additional sources of heat is denoted. Heat flow $q(t)$ arises on the friction surface and penetrates deep into a microlug along a normal to the friction surface. It is given using function $\psi(t) = \dfrac{q(t)\alpha(t)}{\lambda}$.

Thus, it is possible to take into account the non-stationarity of heat flows distributed between the microlug and a semi-space. Correspondingly, function $\varphi(x)$ in the original condition characterizes distribution of temperature at the initial moment of the microlug friction. Since the sizes of the microlug are rather small even relatively to the sliding area, it is considered to be infinite and also the time of contact, with the aim of generalization, infinite too.

In the general form system (4)–(6) is written analytically as the sum of Wiener continual integrals.

$$T(x,t) = x\psi(t) + \int_C \exp\{t\int_0^1 p[|\eta|,\eta_3]d\tau\}\{\varphi[|\eta_1|] - \psi(0)|\eta_1|\}W(dy) +$$

$$+\int_0^t d\sigma \int_C \exp\{(t-\sigma)\int_0^1 p[|\eta|,\eta_2]d\tau\}\{q_1|\eta_1|,\sigma] + \psi(\sigma)|\eta|p[|\eta_1|,\sigma] - \psi'(\sigma)|\eta_1|\}W(dy), \qquad (7)$$

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

and is the Wiener measure.

4. MODELING OF PERIODIC CONTACT OF THE FRICTION SURFACES

A criterion of reaching critical temperature based on physical generalizations is chosen as T_{cr}=0.4–0.6T_{melt}, where T_{melt} is temperature of the microlug melting.

In few papers, devoted to the wave representation of thermomechanical fields, which appear as a result of friction, in most cases periodic or quasi-periodic relief is considered. Comparing such approaches on modeling of the contact surfaces of bodies under friction with the models of A. Chichinadze [4] and Jessim, W. Wiener an analogical feature can be observed. A hard microlug moving over a softer semi-space "cuts" the waves tips on it. This explains the periodical-discrete character of a semi-space over which a microlug or a group of periodically located microlugs is situated. Resulting from the hardness change due to heating an inversion between a semi-space and microlugs can take place when the "cut" areas play the role of more hard inclusions and a semi-space with microlugs located on them become as a result of softening a periodically – discrete surface of sliding. Thus, we can speak about certain temperature waves, caused by periodical structure of the friction surface. We mean here periodical oscillations of heat energy with time and space.

Different approaches to the explanation of causes of the appearance of regular structures on the friction surface are available. For example, their formation is related with friction oscillations. Experimental and theoretical data prove that as a result of friction of even perfect smooth surfaces in the conditions of stabilization an equilibrium periodical or quasi-periodical relief appears on the actual areas of contact of friction bodies fine irregularities. Besides, there is also metallophysical substantiation of the formation of such a fine irregularity.

Though the model is based on a new hypothesis on the release of the surface fine irregularity from the contact with further cooling to the moment of formation of a new contact or in the time span between two subsequent collisions of lugs' pairs within the nominal contact area, it has a number of significant drawbacks. Besides of the unclear criteria of determination of the fine irregularities dimensions, no criterion of determination of irregularity appearance from the contact due to heating, when the accumulation of the interaction energy becomes critical, is provided too. It is unclear what caused the periodicity of the fine irregularity contact and how to relate it with metallographic structure of the friction surface. Moreover, in model no difference is indicated whether a hot spot of the contact appears due to collision of two microlugs of the friction pair surface or whether it is related with relatively long process of sliding of one fine. irregularity over a relatively smooth friction surface. Note also, that the idea of temperature flashes appearance in the process of microlugs collision which later form a single contact spot, was used as a basis of the other model.

Criteria of reaching the critical temperature, primary used in the model of Chichinadze [4] and later in its modification, allow to improve partially some drawbacks of the approaches of B. Jessim, W. Wiener. Correlation of fine irregularities of friction surface microsurfaces and real metallographic microstructure is given in [6]. However, all these papers do not consider a discrete- periodic character of contact that forms the basis of model. Let us unite and develop the previously formulated assumptions.

Likewise, previous models let us assume that a microlug slides over a smooth semi-surface. At the same time let us consider that in the given time span it is in contact with one of the periodically located areas of the friction micro surface. Assume also that a microlug can be out of contact at a temperature of about 0.5 of the melting temperature of the microstructure that formed it.

Decrease of the microlug hardness due to its heating can affect the value of the heat flow: $HB = HB_0 \exp(-kT)$, where HB_0 is hardness of a microlug at room temperature; k is empirical coefficient, T is temperature. To avoid the non-linear problem, hardness change can be modelled not directly with temperature variation, but using its time dependence.

Such cases are possible within the borders of one area:

1. A microlug heats itself due to the effect of temperature splash up to the critical temperature and is leaves the contact.

2. A microlug heats itself to the temperature less that the critical one. In this case the area of a "pit" (no contact is present) it cools down. Assume that the cooling is not complete. Thus, a microlug, when sling over several areas, limited by the real contact area accumulates the energy and after several cycles of heating-cooling, heats itself to the critical temperature and leaves the contact.

3. Temperature of a flash when passing the zone of a "pit" has enough time for cooling to allow the next microlug contact.

In the first case one can directly use the A. Chinchinadze model [4], its modification or a new model based on their basis. In the third case the models can be applied, which are constructed using the principles of fracture mechanic.

In the second case it is possible to use the same equation of heat conductivity with functional coefficients as in the previous model. The process when a microlug, when passing the "pits" cools down, can be described by the following problem.

$$\frac{\partial T_1(x,t)}{\partial t} = a^2 \frac{\partial^2 T_1(x,t)}{\partial x^2} + p(x,t)T_1(x,t) \qquad (0<x,\ t<\infty); \tag{8}$$

$$T_1(x,0) = T_{n_1} \qquad (0 \le x < \infty); \tag{9}$$

$$\frac{\partial T_1(x,t)}{\partial x}\Big|_{x=0} = 0 \qquad (0 \le t < \infty), \tag{10}$$

where T_{n_1} is temperature of a microlug at the moment of completion of the first cycle of sliding over the first contact area of the discreet-regular surface; T_{n_1} is solution of problem (4)–(6) under condition that $T_{n_1} < T_{cr}$, where T_{cr} is critical temperature, at which a microlug leaves the contact.

Analytical solution of problem (8)–(10) has the form

$$T_1(x,t) = x\psi(t) + T_{n_1} \int_C \exp\{t \int_0^1 p[|\eta|, \eta_3] d\tau\} W(dy) + \int_0^t d\sigma \int_C \exp\{(t-\sigma) \int_0^1 p[|\eta|, \eta_2] d\tau\} W(dy). \tag{11}$$

Further, cooling of a microlug to temperature T_{ox}, which is obtained form the solution of system (8) – (10), a problem on heating (4)–(6) is again considered supposing that $\varphi(x) = T_{cool}$. Later the problem on a microlug cooling is formulated again under condition that $\varphi(x) = T_{n_2}$ where T_{n_2} is the temperature at the moment of the second cycle end on the second area and so on. The process of "heating-cooling-heating" continues to the moment when a temperature becomes critical. It is important that cooling is incomplete, that is heat accumulation takes place. Then the time of a microlug existence is found as a sum of continuation of "heating" and "cooling" cycle.

5. CONCLUSIONS

Thus, the given periodic model allows us to generalize, unite and develop the known approaches concerning modeling the temperature flashes.

The problem of calculation of continual integrals is a separate problem. In some cases, they can be reduced to Lebesque integrals. Basically, specially developed approximated methods of calculation of continual integrals are used. Sometimes numerical methods are used for calculation of Lebesque integrals too.

One of the most important problems of temperature flashes modeling is the coordination of such models with real structure of microsurface of the materials of friction pair. Besides, one can rarely compare the results of theoretical calculations with experimental data on determining the value of temperature flashes because of the complicated experiments. At significant values of temperature flashes, and a result of the friction surface temperatures, the change in some physical properties of materials is possible. Special problems are modeling of distribution of heat flows between the friction bodies and also description of the regularities of heat release on the microlevel. Under sliding of a microlug along a semi-space, the diameter of contact spot changes, thus significantly affecting the character of heat release. As a result, the non-linear problems appear. Thus, study of temperature flashes is an important direction in the science on friction – tribology and needs application of new model and experimental approaches.

A LEGEND LIST

ϑ_1 , ϑ_2 – a microlug (i=1) and a semi-space (i=2) temperatures; a_i – heat conductivity coefficients; λ_i – heat conductivity coefficients for a microlug and a semi-space; q_1 and q_2 – intensity of heat flows; directed into a microlug and a semi-, space respectively, z – heat distribution direction; t – time, ρ_1, c_1 и ρ_2, c_2 – density and heat capacity coefficients for a microlug and a semi-space, d_r – diameter of contact spot; ϑ_a^* – initial temperature of a body; υ_0 – velocity of a microlug sliding; HB_2 – semi-space hardness; μ – friction coefficient; p_m – indenter hardness; W – specific loading; A_r – real contact area; $T=T(x,t)$ – temperature flashes; $h(x,t)$ – coefficient of convective exchange; $q_1(x,t)$ – density of heat sources distribution; $q(t)$ – heat flow; $\alpha(t)$ – coefficient of heat flows distribution; $W(\mathrm{d}y)$ – Wiener measure; T_{cr} – critical temperature; T_{melt} – melting temperature; HB_0 – microlug hardness at room temperature; k – empirical coefficient

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