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Frictional heating during braking in a three-element tribosystem

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ABSTRACT

A three-element model of braking process is proposed. In order to determine the temperature fields in each element of the model, the analytical solution of a boundary-value problem of heat conduction for tribosystem, consisting of the semi-space, sliding with the time-dependent velocity (braking at uniform retardation) on a surface of the strip deposited on a semi-infinite foundation, is obtained. The results of the numerical analysis for different materials applied in a braking system, cast iron–FMK-11 metal ceramics–steel, are presented.

1. Introduction

It is well known that mechanical energy is transformed into thermal energy whenever friction occurs. This frictional heating is responsible for temperature increase of the contact surface of bodies and has considerable influence on the tribological behaviour. Therefore, the problem of frictional heat is of a great theoretical and practical interest to researchers.

The heating problems of friction can be examined through a stationary, quasi-stationary and a nonstationary statements. If the slip velocity is low then the convection caused by the motion does not change the temperature and heat fluxes, as well as the process of heat conduction for given external conditions lasting long enough that the influence of initial conditions can be ignored, then in the previous both cases the thermal contact can be assumed as stationary one. A quasi-stationary thermal contact takes place under the condition of sufficiently long duration of friction between bodies being in motion. Whereas, a nonstationary thermal contact is either conditioned by a nonstationary distribution of the contact pressure or by a time-dependent slip velocity as well as by the fact that the development of heating process is considered from some initial time.

The thermal processes during braking are nonstationary and of short duration. A criterion for evaluation of the frictional thermal strength of materials applied in the contacting pairs, in which the principal role plays the temperature of friction has been proposed by Chichinadze [1]. In the latter paper by Chichinadze et al. [2] the following algorithm for calculation of contact temperature for various types of braking systems was proposed:

- maximum temperature rise in the contact surface is given as the sum of the flash temperature and the average temperature of the nominal contact area (or its contour) caused by a heat flux on its surface;
- for calculation of the temperature flash, sliding of a pin on the surface of a smooth semi-space is considered;
- the average temperature is obtained from a solution of a one-dimensional contact problem with transient frictional heat generation.

Generally speaking, the one-dimensional models correspond to those cases when the heat flux can be assumed as normal to the contact surface (Peclet number must be large). The verification of many analytical solutions with the results from the experimental data which refer to the work of the braking devices, shows that the one-dimensional models may be considered as sufficiently good approximation for the computation of the brake systems with heat generation taken into account [3,4]. The theoretical model for average temperature calculation and wear during braking, is proposed in the papers [5,6]. The model is based on the assumption that the friction elements can be treated as a semi-spaces. The assumption is valid when the operating conditions and frictional heating regime are such that a deep layers of the working elements don't have any considerable influence on the contact temperature. But still exist so called heavy friction modes as for example the aircraft brakes systems, when working elements of brakes are heated through their thicknesses. The solution of the heat problem of

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Nomenclature

d	strip thickness
$\mathrm{erf}(x)$	Gauss error function
$\mathrm{erfc}(x) = 1 - \mathrm{erf}(x)$	complementary error function
$\mathrm{ierfc}(x) = \pi^{-1/2}\exp(-x^2) - x\,\mathrm{erfc}(x)$	integral of the error function $\mathrm{erfc}(x)$
f	frictional coefficient
$H()$	Heaviside's step function
K	coefficient of heat conduction
k	coefficient of thermal diffusivity
p_0	pressure
$q = fVp_0$	intensity of the frictional heat flux (the friction power)
T	temperature
$T_{\max}$	maximal temperature
$T_0 = qd/K$	temperature scaling factor
$T^* = T/T_0$	dimensionless temperature
t	time
$t_{\max}$	time, when maximal temperature is reached
t_s	braking time
V	velocity sliding
V_0	initial velocity sliding
z	spatial coordinate

Greek symbols

$\tau = k_s t/d^2$	dimensionless time (Fourier's number)
$\tau_s = k_s t_s/d^2$	dimensionless braking time
$\zeta = z/d$	dimensionless coordinate

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f	bottom semi-space (foundation)
s	strip
t	upper semi-space (top)

friction during braking in the case of the finite thickness of the brakes working elements has been obtained in papers [7,8].

The metal ceramics and mineral-ceramic frictional materials are widespreadily used in brake systems nowadays [9]. This could be explained by their high thermal stability and high wear resistance [10]. A friction patch of a brakes is designed as a thin cermet strip based either on iron or on copper. In the process of braking, this patch is pressed to the counterbody (brake drum, disk, rim of the wheel, etc.). As a result of the friction action on the contact surface, the kinetic energy transforms into heat. The elements of brakes are heated and, hence, the conditions of operation of the friction patches become less favourable: their wear intensifies and the friction coefficient decreases, which may lead to emergency situations [11]. Thus, the problem of heating limitation of is one of the most important in brakes design [12].

In the present paper, we derived the solution of the thermal problem of friction for a tribosystem consisting of three bodies: the upper semi-space (the grey cast iron disk) sliding with the velocity $V(t) = V_0(1 - t/t_s)$, $0 \leqslant t \leqslant t_s$ (braking with constant retardation) on a surface of the strip (FMK-11 cermet frictional element of the patch) deposited on a semi-space (the steel foundation of a patch). The corresponding problem at V = const. (the uniform sliding) has been studied in article [13].

2. Problem formulation

The problem of contact interaction of two semi-spaces is considered, where one of them is homogeneous and the other is a semi-infinite foundation with a strip of thickness d deposited on its surface. The constant pressures p_0 in direction of z axis of the Cartesian system of coordinates $Oxyz$ are applied to the infinities in semi-spaces (Fig. 1). The upper semi-space slides with velocity

$$V(t) = V_0\left(1 - \frac{t}{t_s}\right)H(t_s - t), \quad t \geq 0, \tag{1}$$

in the direction of the y axis on the strip surface. Due to friction, the heat is generated on a contact plane $z = 0$. It is supposed, that the

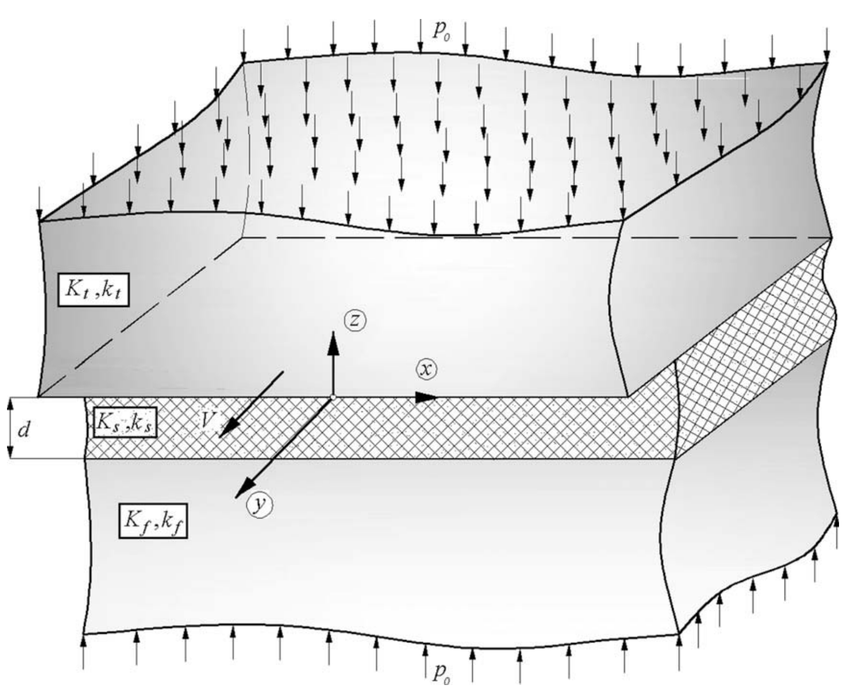

Fig. 1. Scheme of a three-element brake system.