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Influence of thermal sensitivity of the pad and disk materials on the temperature during braking☆

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ABSTRACT

The transient frictional heating of pad–disk tribosystem at single braking is under consideration. To determine the average friction surface temperature, the one-dimensional thermal problem of friction at braking has been formulated. The linear dependence of the thermophysical properties of the disk and pad materials on the temperature has been taken into account. Model of materials with a simple nonlinearity has been adopted, i.e. materials in which coefficients of heat conduction and specific heat depend on the temperature, and their ratio – coefficient of thermal diffusivity – is constant. Linearization of the corresponding boundary-value heat conduction problem by the Kirchhoff transformation and linearizing parameter method has been performed. The numerical–analytical solution to the problem has been found by using the integral Laplace transform and the Newton–Raphson methods. The influence of the thermosensitive materials of titanium pad, sliding over the surface of the disk made of steel, aluminum alloy or gray cast iron, on the temperature has been studied.

1. Introduction

Friction materials used in modern brake systems shall have the highest possible thermal conductivity and heat capacity. Both of these parameters contribute to reduce the temperature of friction: thermal conductivity because of heat dissipation from the surface into the material and then to convection surface, while specific heat because of its absorption [1]. It is well known, that the thermal properties of materials in heavily loaded friction nodes, which also include disk brakes, are temperature dependent [2]. Therefore, calculations of the thermal regime of such friction nodes on the basis of linear mathematical models do not always satisfy the high demands of engineering practice [3]. One way of improving the adequacy of the description of temperature fields, which accompany the braking process, is to develop nonlinear mathematical models of frictional heating, with taking into account thermosensitive materials of friction pair, i.e. dependence of thermophysical properties of materials on temperature [4]. Mathematical models of frictional heating of thermosensitive bodies are represented by nonlinear boundary heat conduction problem, where temperature fields in each body are conjugated by using the boundary conditions on the friction surface. Exact solution to such problems can be obtained in the simplified formulation by introducing a priori the heat partition ratio, i.e. division of heat fluxes between the friction elements and next, consideration of each body separately with heating of their working surfaces by frictional heat fluxes with given intensity [5,6]. Usually, the solution of nonlinear thermal problems of friction at braking is obtained by numerical methods (mainly using FEM) [7–9]. Verification of the results obtained on the basis of FE simulation is usually performed by comparing them with the corresponding experimental data. The process of obtaining data, especially in the last method, is relatively long and costly. Therefore, currently this is an important scientific problem to improve the existing method and to develop new numerical and analytical methods to solve thermal problems of friction for thermosensitive bodies.

The purpose of this article is to obtain a numerical–analytical solution of the thermal problem of friction during braking for thermosensitive disk and pad.

2. Statement of the problem

Let us suppose, that at some point in time, which is taken as the initial $t = 0$, a pad (semi-space $z \leq 0$) is pressed to a working surface of a brake disk (semi-space $z \geq 0$) by a constant pressure in a direction parallel to the z-axis of the Cartesian coordinate system $Oxyz$ (Fig. 1). The sliding velocity of the pad on the disk working surface in the positive direction of the y-axis decreases linearly $V(t) = V_0(1 - t/t_s)$ and $0 \leq t \leq t_s$, where V_0 is the initial velocity and t_s is the stop time. Due to the friction on the friction surface $z = 0$ the heat is generated and the bodies are heated. We assume that:

1) The sum of the intensities of heat fluxes, directed along the normal to the surface of contact inside the semi-spaces, is equal to the specific power of friction $q(t) = f\ V(t)p_0$ [10], where f is the coefficient of friction;

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Nomenclature

a	effective depth of heat penetration;
Bi	Biot number;
c	specific heat;
$\mathrm{erf}(x)$	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	coefficient of thermal conductivity of contact;
K	coefficient of thermal conductivity;
k	coefficient of thermal diffusivity;
p_0	pressure;
$q(t)$	specific power of friction;
T	temperature;
T_0	initial temperature;
T_a	temperature scaling factor;
T^*	dimensionless temperature;
t	time;
t_s	stop time;
V_0	initial sliding velocity;
$V(t)$	sliding velocity;
z	spatial coordinate.

Greek symbols

ρ_l	densities of materials;
Θ	Kirchhoff's variable;
τ	dimensionless time (Fourier's number);
τ_s	dimensionless stop time;
$\zeta = z/d$	dimensionless spatial coordinate;
κ	linearizing parameter;
λ	coefficient.

Subscripts

1	the upper semi-space;
2	the bottom semi-space.

2) The thermal contact of bodies is imperfect, i.e. the heat transfer takes place through the friction surface with a constant coefficient of thermal conductivity of contact h [11];
3) The pad and the disk are made of materials in which coefficients of thermal conductivity K_l and specific heat c_l, linearly depend on the temperature T_l and $l = 1,2$, and their ratio – the coefficient of thermal diffusivity – is constant (materials with simple nonlinearity [12]):

$$K_l(T_l) = K_{l,0}\ K_l^*(T_l),\quad c_l(T_l) = c_{l,0}\ c_l^*(T_l), \tag{1}$$

where

$$K_{l,0} \equiv K_l(T_0), c_{l,0} \equiv c_l(T_0),\quad K_l^*(T_l) \approx c_l^*(T_l) = 1 + \lambda_l(T_l - T_0); \tag{2}$$

4) The densities of materials ρ_l and $l = 1,2$ are constant.

Here and further the quantities relating to the disk and the pad, have subscripts $l = 1$ and $l = 2$, respectively.

Taking into account the assumptions mentioned above we find the distribution of non-stationary temperature fields $T_l(z,t)$ and $l = 1,2$ in the disk and in the pad from solution to the following heat problem of friction:

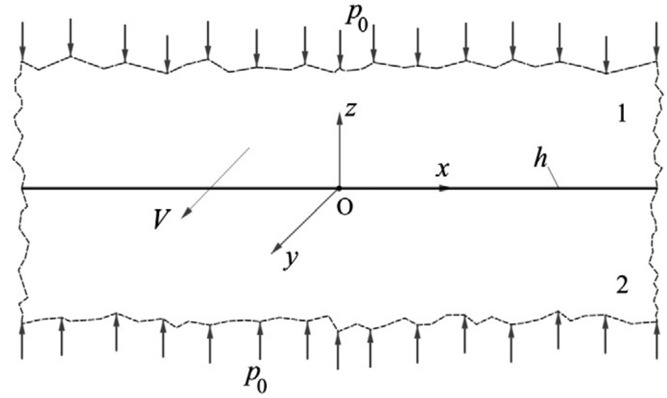

Fig. 1. Scheme of the problem.

$$\frac{\partial}{\partial z}\left[K_l(T_l)\frac{\partial T_l}{\partial z}\right] = \rho_l c_l(T_l)\frac{\partial T_l}{\partial t},\quad 0 < t \le t_s, l = 1,\ 2, \tag{3}$$

$$K_2(T_l)\frac{\partial T_2}{\partial z}\bigg|_{z=0} - K_1(T_l)\frac{\partial T_1}{\partial z}\bigg|_{z=0} = q(t),\quad 0 \le t \le t_s, \tag{4}$$

$$K_2(T_2)\frac{\partial T_2}{\partial z}\bigg|_{z=0} + K_1(T_1)\frac{\partial T_1}{\partial z}\bigg|_{z=0} = h\ [T_1(0,t) - T_2(0,t)],\quad 0 \le t \le t_s, \tag{5}$$

$$T_l(z,t) \to T_0,\quad |z| \to \infty, 0 \le t \le t_s, l = 1,\ 2, \tag{6}$$

$$T_l(z,0) = T_0,\quad |z| < \infty, l = 1,\ 2. \tag{7}$$

Let us denote:

$$\zeta = \frac{z}{a}, \tau = \frac{k_2 t}{a^2},\quad \tau_s = \frac{k_2 t_s}{a^2},\quad K_0^* = \frac{K_{1,0}}{K_{2,0}},\quad k^* = K_0^*\frac{\rho_2 c_{2,0}}{\rho_1 c_{1,0}},\quad Bi = \frac{h\ a}{K_{2,0}}, \tag{8}$$

$$T_a = \frac{q_0\ a}{K_{2,0}},\quad T_0^* = \frac{T_0}{T_a},\quad T_l^* = \frac{T_l}{T_a},\quad l = 1,\ 2, \tag{9}$$

where $a = 1.73\sqrt{k_{2,0} t_s}$ is the effective depth of heat penetration into the disk [1] and $q_0 = fV_0p_0$.

Taking into account formulas (1), (2), (8) and (9), the nonlinear boundary-value heat conduction problem (3)–(7) can be written in dimensionless form:

$$\frac{\partial}{\partial \zeta}\left[K_1^*(T_1^*)\frac{\partial T_1^*}{\partial \zeta}\right] = \frac{1}{k^*}\frac{\partial T_1^*}{\partial \tau},\quad \zeta > 0,\quad 0 < \tau \le \tau_s, \tag{10}$$

$$\frac{\partial}{\partial \zeta}\left[K_2^*(T_2^*)\frac{\partial T_2^*}{\partial \zeta}\right] = \frac{\partial T_2^*}{\partial \tau},\quad \zeta < 0,\quad 0 < \tau \le \tau_s, \tag{11}$$

$$K_2^*(T_2^*)\frac{\partial T_2^*}{\partial \zeta}\bigg|_{\zeta=0} - K_0^*\ K_1^*(T_1^*)\frac{\partial T_1^*}{\partial \zeta}\bigg|_{\zeta=0} = q^*(\tau),\quad 0 \le \tau \le \tau_s, \tag{12}$$