International Communications in Heat and Mass Transfer 87 (2017) 288–294

Contents lists available at ScienceDirect

International Communications in Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ichmt

Influence of thermal sensitivity of the materials on temperature and thermal stresses of the brake disc with thermal barrier coating

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ARTICLE INFO

Keywords:
Friction
Frictional heating
Temperature
Stress
Thermal sensitivity
Thermal barrier coating

ABSTRACT

The time-dependent frictional heating of a disc with applied thermal barrier coating (TBC) on its working surface was investigated. To determine the temperature fields in the coating and the disc a one-dimensional friction heat problem during braking was formulated, with taking into account the dependence of thermal properties of materials from temperature. A model was adopted for materials with a simple non-linearity, i.e. materials whose thermal conductivity and specific heat are temperature dependent, and their ratio – thermal diffusivity is constant. The linearization of the corresponding boundary-value heat conduction problem was made by the Kirchhoff transformation and the linearizing multipliers method. A numerical-analytical solution to the obtained problem was found by Laplace transform method. Knowing the temperature distributions, quasi-static thermal stresses in the strip (TBC) with taking into account change in temperature mechanical properties, were determined. The distribution of temperature and thermal stresses in the strip made from ZrO_2 deposited on the UNS G51400 steel disc, was investigated.

1. Introduction

During emergency braking the temperature of the friction elements on the friction surface may rise even up to 900 °C [1]. Brake discs of modern vehicles due to high speeds have to absorb significant amounts of mechanical energy in a very short time, and they are primarily exposed to destructive influence of high temperature. Brake discs are typically manufactured from conventional materials such as cast iron or carbon steel [2]. The lighter discs made from titanium alloys or aluminium-metal matrix composite [3] are also used. However, all of the above-mentioned materials in heavy-duty braking work modes do not always satisfy the main requirements. One of the way to achieve friction coefficient stability during braking is the application of protective coatings (thermal barrier coatings, TBC) on the friction surfaces [4]. The main task of TBC is to protect the brake disc from high temperatures. Therefore, the most popular property of materials used for TBC, is their low thermal conductivity, as compared to the disc material. Additionally, in selection of brake discs TBC materials operating under high thermal loads, linear coefficients of thermal expansion should also be taken into account. Significant differences of these coefficients for coating materials and the substrate (disc) may cause undesirable cracks on the interface [5].

The most common protective TBC for friction components are ceramic coatings with small thermal and heat coefficients values, and high hardness and wear resistance [6]. Among the wide range of ceramics used to make the brake discs TBC, a special place because of their properties occupy composites on the basis of zirconium dioxide ZrO_2 [7]. It should be noted that the production of TBC from pure ZrO_2 is difficult, because the internal stresses appearing on cooling stage may exceed the tensile strength. Adding so-called stabilizers to zirconium dioxide, such as magnesium oxide MgO, solve the problem. Compound $MgZrO_3$ has low thermal conductivity and a stable coefficient of friction in pair with different friction materials, used in fabrication of pads. Another ZrO_2 stabilizer is the yttrium oxide Y_2O_3. TBC made of a yttrium stabilized zirconia powder (92 ÷ 94% ZrO_2 and 6 ÷ 8% Y_2O_3), is characterized by low thermal conductivity and good resistance to thermal shock, abrasion and corrosion. Therefore, this composite is widely used to made a protective layer of the working surface of brake disc [8,9]. Among other materials used for TBC coating on the surface of the disc, there should be also mentioned an alloy of nickel and chromium Nichrom NiCr, with good thermal properties and high electrical resistance [10].

Convenient tools for investigating the temperature and thermal stresses in the brake discs with TBC are solutions of friction thermal problems during braking for the strip-foundation system. The exact solution of the heat conduction boundary-value problem for the homogeneous strip deposited on the surface of a semi-infinite foundation has been obtained in the paper [11]. It is assumed that the free

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http://dx.doi.org/10.1016/j.icheatmasstransfer.2017.07.021

Available online 24 August 2017

Nomenclature

a	effective depth of heat penetration, (m)
c	specific heat, (J/(kg K))
c_0	specific heat at an initial temperature, (J/(kg·K))
d	thickness of the strip, (m)
E	Young's modulus, (GPa)
k	coefficients of thermal diffusivity, (m^2/s)
K	coefficient of thermal conductivity, (W/(m·K))
K_0	coefficient of thermal conductivity at an initial temperature, (W/(m·K))
q	specific power of friction, (W/m^2)
T	temperature, (°C)
T_0	initial temperature, (°C)
T^*	dimensionless temperature
t	time, (s)
t_s	braking time, (s)
z, y, z	spatial coordinates, (m)
α	coefficient of linear thermal strip material expansion
Θ	Kirchhoff's function
κ	linearizing factors
ρ	specific density, (kg/m^3)
τ	dimensionless time
τ_s	dimensionless braking time
ζ	dimensionless spatial coordinate
ν	Poisson's ratio

Subscripts

1	the strip
2	the semi-space

surface of a strip is heated by a heat flux, with the intensity proportional to the friction force density during braking with a constant deceleration. The obtained solution describes the evolution of the temperature fields, not only during braking, but also during cooling after stop. Solution of a corresponding problem for the composite strip was obtained in the article [12]. Investigation of initiation of the thermal cracking in a homogeneous disc was made in articles [13,14].

All of the above solutions have been obtained under the assumption of constant thermal properties of the TBC and disc. This article attempts to take into account thermal sensitivity of coating and disc materials, which is especially important for the friction nodes operating under high thermal loads (e.g. aircraft disc brakes).

2. Statement of the heat conduction problem

Let us consider the two-element system, consisting of a semi-infinite foundation (body 1), on the surface of which is deposited a strip with a thickness d (body 2). The outer surface of the strip is heated by a heat flux with intensity $q(t) = q_0 q^*(t)$, $0 < t \le t_s$. We assume that the bodies are made of materials with simple nonlinearity – their coefficients of thermal conductivity K_l and specific heat c_l are dependent on temperature T_l, $l = 1, 2$ [15]:

$$K_l(T_l) = K_{l,0} K_l^*(T_l),\; c_l(T_l) = c_{l,0} c_l^*(T_l),\; K_{l,0} \equiv K_l(T_0),\; c_{l,0} \equiv c_l(T_0) \quad (1)$$

where $K_l^*(T_l) \approx c_l^*(T_l)$. The latter ratio, when taking into account the constancy of the specific density of materials ρ_l, $l = 1, 2$ means, that the coefficients of thermal diffusivity are constant and equal $k_l = K_{l,0}/(\rho_l c_{l,0})$. The quantities relating to the strip and foundation will be denoted by subscripts $l = 1$ and $l = 2$ respectively.

We assign the considered two bodies system to the Cartesian coordinate system $Oxyz$ (Fig. 1). Distribution of non-stationary temperature fields $T_l(z,t)$ in the strip ($l = 1$) and the foundation ($l = 2$) we find from the solution of nonlinear boundary-value heat conduction problem:

$$\frac{\partial}{\partial z}\left[K_1(T_1)\frac{\partial T_1}{\partial z}\right] = \rho_1 c_1(T_1)\frac{\partial T_1}{\partial t},\; 0 < z < d,\; 0 < t \le t_s, \quad (3)$$

$$\frac{\partial}{\partial z}\left[K_2(T_2)\frac{\partial T_l}{\partial z}\right] = \rho_2 c_2(T_2)\frac{\partial T_2}{\partial t},\; z < 0,\; 0 < t \le t_s, \quad (4)$$

$$K_1(T_1)\frac{\partial T_1}{\partial z}\bigg|_{z=d} = q(t),\quad 0 < t \le t_s, \quad (5)$$

$$T_1(0,t) = T_2(0,t),\quad 0 < t \le t_s, \quad (6)$$

$$K_1(T_1)\frac{\partial T_1}{\partial z}\bigg|_{z=0} = K_2(T_2)\frac{\partial T_2}{\partial z}\bigg|_{z=0},\quad 0 < t \le t_s, \quad (7)$$

$$T_2(z,t) \to T_0,\; z \to -\infty,\quad 0 < t \le t_s, \quad (8)$$

$$T_l(z,0) = T_0,\quad z \le 1,\quad l = 1,\; 2. \quad (9)$$

Designating

$$\zeta = \frac{z}{a},\quad \tau = \frac{k_1 t}{d^2},\quad \tau_s = \frac{k_1 t_s}{d^2},\quad K_0^* = \frac{K_{2,0}}{K_{1,0}},\quad k^* = \frac{k_2}{k_1},\quad T_a = \frac{q_0 d}{K_{1,0}},\quad T_0^* = \frac{T_0}{T_a},\quad T_l^* = \frac{T_l}{T_a},\quad l = 1, 2, \quad (10)$$

boundary heat conduction problem Eqs. (3)–(9) can be written in dimensionless form:

$$\frac{\partial}{\partial \zeta}\left[K_1^*(T_1^*)\frac{\partial T_1^*}{\partial \zeta}\right] = \frac{\partial T_1^*}{\partial \tau},\; 0 < \zeta < 1,\; 0 < \tau \le \tau_s, \quad (11)$$

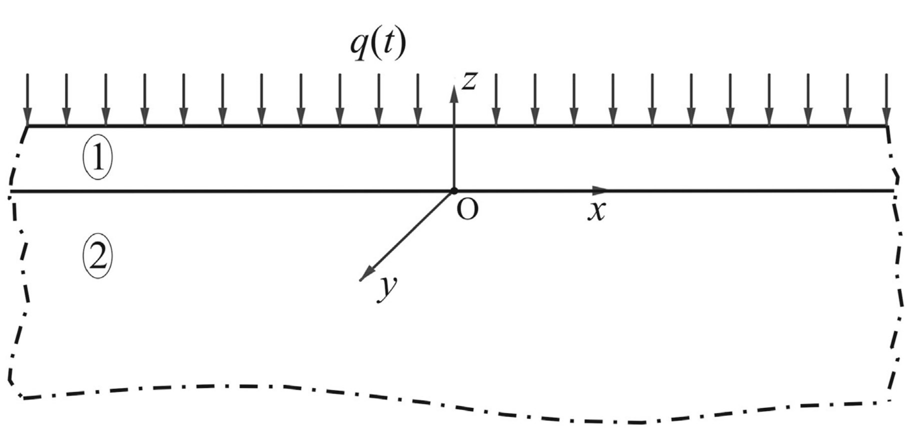

Fig. 1. Scheme of the problem.