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Three-dimensional FE model for calculation of temperature of a thermosensitive disc

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HIGHLIGHTS

► FE simulation for 3D nonlinear heat conduction problem of friction was developed.
► Temperature-dependent thermophysical properties of materials of the pad/disc system.
► Insensitivity of temperature dependence of heat partition ratio on the temperature.
► An effect of thermal diffusivity of aluminium alloy series Al MMC on the temperature.

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ABSTRACT

An effect of variations of the temperature-dependent thermophysical properties of materials of a pad and a disc on the temperature generated due to friction was studied. A three-dimensional boundary-value problem of heat conduction of the disc heated locally within the contact area by the moving with the constant deceleration heat flux and the intensity proportional to the specific capacity of friction was formulated. An issue was solved numerically using the finite element method (FEM). The experimental dependences curves of the thermal conductivity and the thermal diffusivity on the temperature ranging from 20 to 500 °C indispensable for the calculations were approximated using Chichinadze's methodology. The comparative analysis of temperature values on the contact surface of the disc obtained with and without influence of temperature dependence of the four different pad and the same quantity of the disc materials was carried out. It was demonstrated that apparent temperature differences arose for each friction couple combining temperature-dependent and constant properties of materials, however, the largest observed discrepancy (13.7%) occurred for the disc made of aluminium alloy series Al MMC. Other disc materials i.e. iron alloy series FCD50, cast iron ChNMKh and steel EI-696 revealed relatively equal temperature differences of order of 6.4%. Furthermore incorporated in the formula for the heat partition temperature variability of the thermophysical properties of materials affected the resulting contact temperature of the disc for friction couple combined exclusively with the titanium pad VT-14 (3.1%).

1. Introduction

Disc brakes have now become the most commonly used brakes in vehicles, aircrafts, and many other devices due to their numerous advantages. However constantly increasing requirements for the brake systems for safety, durability, reliability, with the concurrent decrease in the cost of the production process, contribute to the continuous extension of the base of materials for friction elements in the pad/disc system. The selection of such materials, which would, in particular, secure the stability of coefficient of friction with minimal wear of contacting surfaces, is impossible without taking into account the calculations of the temperature regime of the brake system [1].

Carrying out calculations of temperature it is necessary to take into account the specificity of working of a given friction couple, namely the regime of its working (short or long, single or multiple), the nature of cooling, magnitudes and their variations with time of thermophysical properties of friction materials, heat partition ratio and the surface area of contact. The dynamically varying during friction parameters of operation of braking for the brakes make it difficult to formulate a universal model, allowing to determine the temperature distributions at any moment in time either during a deceleration time or after a standstill. Therefore in each particular case the factors that might have the greatest impact on the heating process and those which may be ignored must be specified. This would allow to simplify significantly a solution to the corresponding heat problem of friction during braking [2].

The use of the finite element method (FEM) for solving linear boundary-value problems of heat conduction at present is based on

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Nomenclature

c	specific heat, J/(kg K)
$[C]$	heat capacity matrix
f	coefficient of friction
h	heat transfer coefficient, W/(m^2 K)
k	thermal diffusivity, m^2/s
K	thermal conductivity, W/(mK)
$[K]$	heat conduction matrix
p	contact pressure, Pa
q	intensity of heat flux, W/m^2
$\{Q\}$	vector of applied heat loads
r	inner radius, m
r_{mean}	mean radius of the rubbing path, m
R	outer radius, m
t	time, s
t_s	braking time, s
T	temperature, °C
T_a	ambient temperature, °C
T_0	temperature at the initial moment of time, °C
Δt	time step for finite element calculations, s
$\{T\}$	temperature vector
V_0	initial vehicle speed, km/h
Δx	element dimension, m
z	axial coordinate, m

Greek symbols

γ	heat partition ratio, m
δ	thickness, m
ρ	density, kg/m^3
θ	circumferential coordinate, deg
θ_0	pad arc length, deg
ω	angular sliding speed, 1/s
ω_0	initial angular sliding speed, 1/s

Subscripts

d	indicates disc
p	indicates pad
w	indicates wheel

the axisymmetric models (2D), in which the relative slip speed effect reveals in the averaged intensity of heat flux on the circumference of the rubbing path of the rotor [3–6] or on the spatial models (3D) [7–9]. A review paper on the applications of FEM to determine temperature in the pad/disc frictional system was made in article by Yevtushenko and Grzes [10].

The difficulties in the mathematical and numerical formulation accounting for the nonlinear character of changes of the parameters during friction process such as a temperature-dependent coefficient of friction, or an effect of thermosensitivity of materials on the generated during friction temperature, constitute a major disadvantage in relation to the accuracy of the results. Furthermore, obtained so far solutions are mainly two-dimensional models [11,12] or an area of calculation includes a segment of a brake [13]. Papers concerning calculations for fully three-dimensional models often do not include an effect of unequivocally non-uniform heat load on an axisymmetric disc by a pad completely covering the rubbing path [14].

A nonlinear inverse problem to estimate the unknown space- and time-dependent heat flux was studied in article [15]. The computations were carried out based on numerical procedure employing the unstructured-mesh, fully collocated, finite-volume code, 'USTREAM' Bering the descendent of the structured-mesh, multi-block code of 'STREAM' [16]. The determined temperature distributions obtained from the direct problem were used to simulate the measurements of temperature. It was observed that despite the fact of considerable range of temperature variations, the maximum temperature-difference between the values based on calculations accounting for the temperature-dependent properties of material and values obtained by means of temperature-independent were of order of 2%.

In this paper, previously developed linear 3D solution for the heat problem of friction during braking [6,9] was extended to the nonlinear case with a temperature-dependent thermal conductivity and a specific heat of the pad and the disc materials.

2. Statement of the problem

Let at the initial time moment $t = 0$ the disc is rotating with an angular speed ω_0 and the pads that are pressed against an outboard and an inboard surface of the disc generate the constant contact pressure p within the area of relative contact. Furthermore a problem due to the symmetry about the mid-plane of the disc is simplified ignoring half of the entire disc and one pad. The friction opposes motion and the angular speed of the disc ω decreases linearly with time from nominal value ω_0 to the zero at the stop time moment $t = t_s$:

$$\omega(t) = \omega_0\left(1 - \frac{t}{t_s}\right), 0 \le t \le t_s \tag{1}$$

The heat due to friction on the contact surfaces is generated, which in the form of the heat flows goes on heating of the pad and the disc. The sum of intensities of these heat fluxes is equal to the specific capacity of friction. On the free surfaces of the disc the convective cooling with constant heat transfer coefficient takes place, whereas the surface denoting mid-plane of the disc is insulated. The radiation mode of heat transfer is omitted since its share in heat dissipation during a single braking process is negligible. Materials of the pad and the disc are thermosensitive, i.e. their thermophysical properties are temperature-dependent.

We relate the considered pad/disc tribosystem with the cylindrical coordinate system (r,θ,z) (Fig. 1). Under the abovementioned assumptions we find the three-dimensional transient temperature fields $T(r,\theta,z,t)$ in rotating disc from the solution of the following nonlinear boundary-value heat conduction problem:

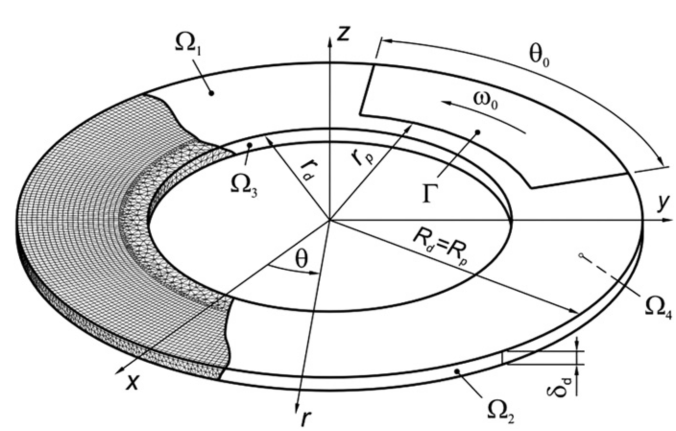

Fig. 1. Diagram of a disc brake with the finite element mesh and boundary conditions.