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Mutual influence of the sliding velocity and temperature in frictional heating of the thermally nonlinear disc brake

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ABSTRACT

Transient temperature fields in sliding components of a disc brake at coupling of temperature-dependent coefficient of friction, thermophysical properties of materials, time-dependent contact pressure and a velocity were analysed using the finite element method (FEM). Simulation of a single braking process for a cast-iron disc (ChNMKh) and a pad made of FMC-11 at four values of the contact pressure was carried out. Dependencies of the coefficient of friction and thermophysical properties of materials were adopted from experimental data. The temperature fields, braking times, and braking distances were calculated and confronted with the cases at the constant coefficient of friction.

1. Introduction

Temperature plays an important role in disc brakes due to large amount of mechanical energy converted into heat at deceleration of vehicles, aircrafts, mine hoists, etc. A solution for thermal problem of friction can be obtained using analytical methods, but only for simplified geometrical objects (semi-spaces, strips, etc.). Approximate solutions for complex objects are being obtained by means of numerical methods. A review of studies of temperature and thermal stresses in disc brakes and clutches using FEM were given in the article [1].

A change in temperature affects mechanical and physical properties of materials of the sliding components, which then vary conduction heat transfer and the ratio of separation of heat generated due to friction. An influence of thermosensitivity of the properties of materials on temperature fields in the pad and the disc during a single braking process was studied in the articles [2,3]. It was found that the maximum temperature reached at 'constant' and thermosensitive materials differed to 25%. A three-dimensional FE model of an aircraft brake made of C/SiC composite material was developed in Ref. [4]. An influence of the initial velocity, deceleration and the coefficient of friction on the maximum temperature taking into account temperature-dependent properties of materials were studied.

In general case a change in contact pressure depends on the system considered (hydraulic, pneumatic, mechanical, electromagnetic, etc.) as well as on the conditions of application of a brake. The change in contact pressure may be determined from the equation of motion and using experimental dependencies of the contact pressure on time [5–7]. A system of thermal dynamic of friction at known evolution of contact pressure and the thermal problem of friction at imperfect contact of a pad and a disc was solved using a Laplace transform in the article [8]. A generalization of that solution was obtained in the article [9]. However, in calculations of temperature either analytical or numerical, even when the contact pressure applied varies with time, it is assumed that it does not have an influence on the velocity (linear decrease is assumed) [10,11]. Frequently the contact pressure is constant [12]. More actual is an approach, in which the velocity is found based on the change in the pressure and then it is applied in computations as known conditions independent on any parameters varying during braking (temperature, properties of materials, coefficient of friction) [13,14].

During braking heat generated due to friction is transferred to the neighbouring parts of the assembly through conduction and then dissipated by convection and thermal radiation. Depending on

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Nomenclature

A_p	nominal area of the friction surface of the pad, m^2
c	specific heat, J/(kg K)
f	coefficient of friction, dimensionless
f_{av}	average value of the coefficient of friction, dimensionless
f_0	coefficient of friction at temperature of 20 °C, dimensionless
F	total time-dependent friction force from disc brake systems, N
h	heat transfer coefficient, W/(m^2 K)
K	thermal conductivity, W/(m K)
k	thermal diffusivity, m^2/s
m	mass of a vehicle, kg
p	contact pressure, Pa
p_0	nominal value of the contact pressure, Pa
q	specific power of friction, W/m^2
Q	power of friction, W
r	radial coordinate, m
r, R	inner and outer radius, respectively, m
R_w	outer radius of the wheel, m
r_{eq}	equivalent radius of the rubbing path, m
S	braking distance, m
t	time, s
t_m	growing time, s
t_s	braking time, s
Δt	time step, s
T	temperature, °C
$\overline{T}$	temperature on the contact region, °C
T_a	ambient/initial temperature, °C
V	vehicle velocity, m/s
V_0	initial vehicle velocity, m/s
z	axial coordinate, m

Greek symbols

δ	thickness, m
θ	circumferential coordinate, rad
θ_0	cover angle of the pad, rad
ρ	density, kg/m^3
τ	time, s
ω	angular velocity of the disc, s^{-1}
Ω	contact region, m^2

Subscripts

d	indicates disc
p	indicates pad

Superscripts

$\pm$	values, obtained at the approach to plane $z = 0$ along positive $(+)$ or negative $(-)$ direction of the axis

the system and operating parameters considered, two latter of these modes of heat transfer may either play significant role or be neglected. However convection for most cases of braking is taken into account, the thermal radiation ought to be incorporated particularly at extreme temperature – it appears in the power of the fourth. Also emissivity of the smooth/polished surfaces of the metal rotors is low.

Convective heat transfer requires a detail analysis since the phenomenon is complex. It is characterized by dimensionless parameters (Nusselt, Reynolds, Prandtl numbers). Different radial temperature profiles for an internally heated disc were examined in the article [15]. In order to find Nusselt numbers numerical calculations based on Laplace's equation were carried out parallel to the measurements using fluxmeters.

Numerical calculations of the heat transfer coefficient for the thin rotating disc subject to an airflow were given in Ref. [16]. The calculations of the flow and temperature fields around the disc were obtained by means of large-eddy-simulations (LES). Different rotational velocities of the disc and velocities of airflow parallel to the plane of rotation of the disc were studied.

A 3D thermomechanical contact model of a disc brake of a vehicle to study temperature fields and thermal stresses was developed in Ref. [17]. It was assumed that the applied force, coefficient of friction and properties of materials are constant. An emphasis was placed on taking into account variation of the heat transfer coefficient. A comparative analysis of temperature changes and the heat transfer coefficient obtained using a solid and a ventilated type of a brake disc was carried. For the solid type of a disc, the calculated convective heat transfer coefficient for extreme conditions varied from 0 to 120 Wm^{-2} K^{-1}.

A 3D FE analyses of temperature fields obtained for a solid type of a disc at single and repetitive braking (heat transfer coefficients $0 \div 100$ Wm^{-2} K^{-1}) were carried out in the articles [18,19]. It was found that during a short single braking at constant speed of sliding the maximum temperature difference obtained at the extreme values $h = 0$ (adiabatic condition on free surfaces) and $h = 100$ Wm^{-2} K^{-1} (forced convection by airflow) did not exceed 3%. That fact validates typical approach in establishing the convective conditions during short emergency braking of a passenger vehicle, where constant average value is taken, e.g. 60 Wm^{-2} K^{-1} [20].

Temperature field in a brake disc for coal mines using a code based on finite volume technique was studied in the article [21]. The authors proposed an approach employing the Lagrangian analysis in order to vanish a material derivative in the problem statement. A simulation of frictional heating of the disc was carried out at constant angular speed. Both thermal radiation and convective cooling were considered. The obtained results were confronted with the experimental outcomes.

Coefficient of friction during braking should be high and independent of contact conditions. This approves controllability of the friction force and therefore safety of exploitation. Its value, however, may be influenced by a slip velocity, contact pressure, temperature, etc. Particularly the latter from these parameters affects the fluctuations of the resulting friction force and in turn the slip velocity, time and distance of braking. Accounting for the coupling between the temperature-dependent coefficient of friction and the velocity requires mutual solution of equation of motion and the heat conduction equation.

A detail analysis of influence of material properties on the contact pressure and temperature fields of sliding bodies was carried out by Thuresson [22]. The model consisted of the elastic rectangular block (friction material) slipping on the rigid foundation. On the free surfaces of the block convective cooling took place. It was assumed that the coefficient of friction decreases linearly with temperature, which corresponds with the phenomenon known as a brake fade. A 3D thermomechanical FEA of temperature fields and thermal stresses in a solid and ventilated brake disc at