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The numerical–experimental scheme for the analysis of temperature field in a pad-disc braking system of a railway vehicle at single braking☆

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ABSTRACT

A single braking process based on actual dimensions of the sliding components of the railway braking system, operating parameters, and properties of materials is analysed. The cast-iron brake disc combined with the pads made of the advanced organic composite material were examined. First, the properties of the friction material using the pulsed infrared (IR) thermography were determined. In the next step, the numerical FE solution to the thermal problem of friction for the pad-disc braking system was obtained. The calculated changes in transient temperature fields of the pad and the disc during braking were presented. Then the calculated numerically maximum temperatures for the series of different parameters, mass per wheel, initial velocity, coefficient of friction, applied load were compared with the corresponding measured values using thermocouples embedded in the disc. Based on the presented outcomes, the proposed numerical–experimental scheme for the analysis of temperature in the railway braking system was verified.

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1. Introduction

Braking of vehicles relies on a dissipation of its kinetic energy. Such process is done by a mutual slipping of contacting components of a braking system. The kinetic energy is dissipated as heat, which increases the temperature of the friction surfaces.

The most commonly used braking systems in railway vehicles, particularly in high-speed trains, are disc brakes, where the immovable pads slide against the rotating disc. The disc brakes frequently operate near the critical values of temperature and/or concurrent formation of hot spots, which in turn may cause deformations of a disc, thermal cracks, degradation of a friction material, brake fluid vaporization, etc. The development of hot spots was first investigated by Barber [1,2]. In the pioneering studies the author made an attempt to describe the mechanisms of the feedback between the thermal deformation and the contact pressure distribution (thermoelastic instability—TEI) leading above a critical speed to hot spots on the rubbing path.

A more recent insight into the generation of hot spots was made by Panier et al. [3]. The authors focused on complex measurements of temperature in the railway disc brakes on a test bench using infrared camera. Based on the obtained results, the main types of hot spots were classified as well as the type of hot spots being the most responsible for damages of the discs were established.

Experimental study of hot spots and third body formation for two-disc friction couple made of sapphire and steel were conducted by Majcherczak et al. [4]. The measurements were performed using infrared camera and thermocouples. In addition, the numerical finite element (FE) model for temperature calculation was developed. Unlike typical approach assuming equality of temperature on the interface of contacting bodies, in this paper, a thin layer representing a third body was introduced. But an analysis of the thermal problem was carried out without taking into account mechanical interactions. It was shown that the pad contact temperature is higher than the disc temperature due to thermal resistance of the third body.

The calculations of temperature fields in components of railway disc brakes have been developed in parallel to the road vehicle and aircrafts disc brakes. Analytical methods give exact solutions; however, they are restricted to specific geometrical objects such as strips or semi-spaces [5]. In addition, there is a difficulty in application of nonlinear problems due to the temperature dependence of the properties of materials or other quantities varying with temperature (e.g. coefficient of friction). Numerical methods (e.g. the finite element method) are free from these drawbacks; nonetheless, they allow to obtain only approximate solutions. So far, various models to determine the temperature in sliding components and approaches have been proposed and examined. The FE modelling of temperature fields and thermal stresses in disc brakes and clutches was analysed in review articles [6,7].

A three-dimensional numerical model of a wheel mounted solid brake disc with one side heated was proposed by Tirovic [8]. The advantages and disadvantages of using such type of disc compared to bilaterally heated axle mounted disc were given and discussed. The main

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Nomenclature

A_p	Nominal area of the contact region, m^2
c	Specific heat, J/(kg K)
f	Coefficient of friction, dimensionless
F_1	Total clamping force on the pads at time t_1, N
F_2	Total average clamping force on the pads at the distance S_2, N
d	Thickness of the material at thermal diffusivity measurement, m
h	Heat transfer coefficient, W/(m^{2}K)
K	Thermal conductivity, W/(m K)
k	Thermal diffusivity, m^2/s
m	Mass of the disc, kg
M	Simulated mass per one disc brake, kg
p	Contact pressure, Pa
q	Specific power of friction, W/m^2
r	Radial coordinate, m
$r,\ R$	Inner and outer radius, respectively, m
r_{eq}	Equivalent radius of the rubbing ring (pad), m
r_m	Radius at the centre of the pad, m
R_w	Outer radius of the wheel, m
S	Total braking distance between V_0 and V_s, m
S_2	Braking distance between V_1 and V_s, m
t	Time, s
t_1	Time of reaching 95% of total clamping force, s
$t_s = t_1 + t_2$	Total braking time, s
Δt	Time step for numerical analysis, s
T	Temperature, °C
$\overline{T}$	Temperature on the contact region, °C
T_0	Initial temperature, °C
T_c	Maximum temperature (calculated) at $r = 0.287$ m, $\theta = 2.329$ rad, $z = -0.001$ m, °C
$T_1 \div T_6$	Maximum temperature of the disc measured by thermocouples $1 \div 6$, °C
V	Vehicle velocity, km/h
V_0	Initial velocity of the vehicle, km/h
V_1	Vehicle velocity at time t_1, km/h
V_s	Vehicle velocity at time t_s, km/h

Greek symbols

α	
δ	Thickness, m
θ	Circumferential coordinate, rad
ρ	Mass density, kg/m^3
ω	Angular speed of the disc, rad/s
Γ	Contact region of the pad and the disc
Ω_p	Region within the volume of the pad
Ω_d	Region within the volume of the disc

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

purpose was to design a new brake disc achieving the lowest temperature, deflection, and thermal stresses during single braking. Due to symmetry of the disc, the computational region was restricted to 7.5° section.

An attempt to indicate the mechanisms leading to cracking of high-speed railway brake discs was made in the paper [9]. The solid disc from the boogie trailer mounted on the axle was analysed. Two pads of the braking system consisted of nine pins were located on the opposite friction surfaces of the disc. The authors carried out several steps investigation using numerical models and experimental measurements. It was shown that the mechanical loads are negligibly small compared to the thermal one. The hot spots located periodically in the circumference of the friction surface were modelled as heat flux densities with variable distribution within one spot. The results were confronted with the experimental data of temperature fields.

The interactions within the sliding components of the railway brake disc with respect to the scale of the phenomenon were studied in the article by Dufrénoy [10]. The aim was to provide the reliable information of mutual relations of thermomechanical behaviour of the brake, wear of the pad with real shape and dimensions. One of the point was to use a hybrid two-/three-dimensional model. A detail analysis of the fluid flow in radial vane/pillared discs brakes using CFD was carried out by Tirovic [11]. The author emphasised the problem of energy saving for different ventilated axle mounted brake discs for high-speed trains.

A wheel mounted vented brake disc temperature was analysed numerically using FEM in the article by Ghadimi et al. [12]. The obtained results were verified experimentally on a inertial test rig. In the developed computational model of a brake, it was assumed that the pad area is spread within the entire circumference of the friction surface—average value of the heat flux density was applied. The separation of heat between the pad and the disc was governed by the constant value determined from the formula for the heat partition ratio. The calculations were performed for five values of deceleration to identify its influence on the maximum temperature. Based on that, computational model thermal stresses were computed and analysed in the article [13].

Constantly growing requirements for the friction materials such as consistent coefficient of friction, durability, tribological compatibility with the material of the rotor, cost-efficiency at the design stage, to be environmentally friendly, promote the formation of advanced materials and new methods of measurement of their characteristics [14]. Considering a new material, the properties crucial for estimation of temperature (e.g. thermal diffusivity) are not known and should be determined. Analysing the heat conduction problem, three out of four thermophysical properties have to be known (specific heat, density, and interchangeably thermal conductivity or thermal diffusivity). The specific heat and the density may be obtained relatively easily. The difficulty is in finding a thermal conductivity or a thermal diffusivity. The method of measuring of thermal diffusivity by means of the pulsed IR thermography was proposed in the article by Kochanowski et al. [15].

The presented work deals with the comprehensive analysis of transient temperature fields in the pads made from a new advanced organic composite material and in the disc of a railway brake during a single braking process. The main goal was to develop an FE model of the disc brake, which allows to evaluate reliable temperature fields in the sliding components coincident with the experimental data within the wide range of operating parameters. In order to carry out numerical simulation of heat generation, a thermal diffusivity of the friction material was determined by means of the pulsed IR thermography. The comparisons of the maximum temperature calculated with the results obtained from the measurements made it possible to check the correctness of the model used and to validate the proposed method of determination of the thermal diffusivity.

2. Statement of the problem

The object of the study was a vented brake disc commonly used in locomotives or coaches. The braking system consists of two pads and the disc. At the initial point in time $t = 0$ under the influence of clamping force F, the pads are pressed to the rubbing surfaces of the disc. The

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