THREE-DIMENSIONAL FE MODEL OF FRICTIONAL HEAT GENERATION IN A DISC BRAKE

Piotr Grzes [a)], Adam Adamowicz & Aleksander Yevtushenko
Faculty of Mechanical Engineering, Bialystok University of Technology, Bialystok, Poland

Summary A transient FE simulation of frictional heat generation for three-dimensional non-linear heat conduction problem was developed. An influence of a number of parameters of the process such as the velocity of the vehicle, the intensity of convective heat exchange, the contact pressure incorporating the temperature-dependent thermal conductivity and the specific heat of the materials of the temperature were studied. Individual relationships of the factors with the resulting temperature of the disc are confronted and discussed.

INTRODUCTION

Slipping process of two bodies being in contact leads to the heat generation due to friction. An effect is particularly evident in brakes. The most commonly used type are disc brakes whose numerous advantages such as stability of friction force and its relatively high magnitude displace other construction types and contribute in successive improving in safety, durability and reliability of the exploitation process. Since the operation parameters such as the braking time, the number of applications, the initial speed and rate of deceleration, the convective cooling conditions, the dimensions of the brake system may vary firmly, the frictional heat generation constitutes a major difficulty in formulating universal physical model. Thereby it is important to distinguish these factors that are crucial for the given friction couple. Among a variety of numerical methods for calculation of heat conduction problem of friction, finite element method (FEM) has become the most efficient and applicable method for relatively complex geometries such as disc brakes. A review paper on the FEM investigation of the transient temperature distributions in a pad/disc tribosystem based on the solution of linear parabolic heat conduction equation is presented in article [1]. Nowadays two models of heat generation problem for the pad/disc systems are typically studied – an axisymmetric (2D) and a three-dimensional (3D). FE solutions of axisymmetric problem can be found in article [2]. The three-dimensional FEA of the temperature distributions in the pad/disc system was carried out in [3,4] for single braking and for repetitive brake application in [5]. In this study the three-dimensional FE model for non-linear heat conduction problem of friction is developed.

STATEMENT OF THE PROBLEM

When the braking process occurs the friction between the disc and the pads opposes motion and the speed of the vehicle decreases. The generated heat is dissipated through conduction from the pad/disc interface. On the exposed surfaces of the brake system convection with the constant heat transfer coefficient takes place. The radiation mode of heat transfer is neglected due to relatively low temperatures and short time of the braking process. As for the symmetry of the problem about the mid-plane of the disc, the analysed region is limited to the half of the entire disc of thickness δ_d and one pad. Furthermore only disc temperature distributions are analysed. It is assumed that the angular sliding speed decreases linearly from the initial value ω_0 to zero at the stop time moment. The real surface of contact between the disc brake and the pad during braking is equal to the apparent surface, hence the contact pressure p_0 that acts on the friction surface is uniform and independent of the thermal state of the system. The properties of materials are temperature-dependent.
Since the rotational motion of geometrically symmetric disc and axisymmetric stationary pads generate non-uniform temperature distributions, the problem is three-dimensional. To evaluate the temperature distributions, both analytical and numerical techniques have been employed. The starting point for the analysis of the temperature field in the disc was the parabolic heat conduction equation given in the cylindrical coordinate system (r, θ, z)

$$\frac{1}{r}\frac{\partial}{\partial r}\left(rK_d(T)\frac{\partial T}{\partial r}\right)+\frac{1}{r^2}\frac{\partial}{\partial \theta}\left(K_d(T)\frac{\partial T}{\partial \theta}\right)+\frac{\partial}{\partial z}\left(K_d(T)\frac{\partial T}{\partial z}\right)=\rho_d\, c_d(T)\left[\frac{\partial T}{\partial t}+\omega(t)\frac{\partial T}{\partial \theta}\right], \tag{1}$$
$$r_d < r < R_d, 0 \le \theta \le 2\pi, 0 < z < \delta_d, t > 0,$$

where: K – is the thermal conductivity, T – is the temperature, θ – is the circumferential coordinate, z – is the axial coordinate, ρ – is the density, c – is the specific heat, r – is the inner radius, R – is the outer radius, t – is the time, d denotes the disc.

SOLUTION TO THE PROBLEM

An issue of mutual contact of the pad and the disc is accomplished by local heating of the rubbing path of the disc moving with the intensity proportional to the specific capacity of friction. The periodic pad transition resulting in

[a)] Corresponding author. Email: p.grzes@doktoranci.pb.edu.pl.

gradual covering of the specific spot on the contact surface of the disc was developed using Python Programming Language [6]. The boundary thermal flux including interchangeably varying cooling conditions for every element of the mesh (owing to the radial and the circumferential location on the rubbing path) for the specific time t was calculated. The timing charts for the specified finite elements arose directly from the incorporated gradual covering by pad from the value of 0 (pad outside an element) to 1 (full covering by the pad).
The problem was solved using finite element method. In order to obtain matrix form of Eq. (1) the Galerkin's approach was used

$$[\mathbf{C}]\frac{d}{dt}\{\mathbf{T}\}+[\mathbf{K}]\{\mathbf{T}\}=\{\mathbf{Q}\} \tag{2}$$

where: $[\mathbf{C}]$ – is the heat capacity matrix, $[\mathbf{K}]$ – is the heat conduction matrix, $\{\mathbf{T}\}$ – is the temperature vector, $\{\mathbf{Q}\}$ – is the vector of applied heat loads.
To accomplish for the non-linearity arising from the temperature-dependent thermal conductivity K and the specific heat c numerical integrations method with iterations at each time step was used [7]. Based on the experimental data [8,9] the temperature dependences of the four materials of the disc: Al MMC (aluminum alloy series), FCD50 (iron alloy series), steel EI-696, cast iron ChNMKh and four materials of the pad: the metal-ceramics FMC-11, FMC-845, MCV-50, and titan VT-14 of the thermal conductivity $K(T)$ and the thermal diffusivity $k(T)$ of the temperature were found using approximation procedure proposed in [10]. The temperature evolutions on the contact surface of the disc obtained with and without influence of temperature dependence were confronted and compared.
In the next stage of the research FE model of a disc was restricted to the case with temperature independent thermophysical properties of materials focusing on the influence of the convective cooling on the resulting temperature distributions of the disc during single and multiple braking process with constant speed of the vehicle of 100 km/h. The calculations were performed for the convective heat transfer coefficient h ranging from 0 to 100 W/(m^{2}K). The computations with the step of 10 W/(m^{2}K) were repeated for different number of brake applications to identify its influence on the maximum temperature of the considered process and the temperature attained at the end of braking.

CONCLUSIONS

The transient FE simulation of frictional heat generation for three-dimensional non-linear heat conduction problem was carried out. It was exhibited that the temperature differences occur for every of the studied friction couples distinguishing temperature dependent and constant thermophysical properties of materials, however, the largest discrepancy (13.7 %) was attained for the disc made of aluminum alloy series Al MMC. It was attributed to the thermal diffusivity whose decrease with the temperature was dominant among studied materials. The corresponding temperature difference for other materials of the disc was of order of 6.4 %. Furthermore it was demonstrated that except the titanium pad VT-14 (3.1 %) the heat partition between the pad and the disc is insensitive to temperature dependence of the pad and the disc materials.
The corresponding computations carried out for the thermophysical properties of materials independent of the temperature revealed that that highest temperature difference for contrast cooling conditions give an error lower than 3 %, which support the claim that the convective cooling does not allow to lower significantly the temperature of the disc during braking. For the multiple braking process with the constant velocity the maximum attained temperature decreases with the increase in brake applications, whereas the opposite situation takes place for the temperature at the end of the process. Both the maximum temperature as well as the temperature reached at the end of the braking process on the contact surface decreases with the increase in the intensity of cooling. The relation was found to be linear, whereas the slope of the curve was dependent on the number of brake applications.

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