SOME ANALYTICAL MODELS OF FRICTIONAL HEATING DURING BRAKING

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Summary The paper presents the analytical solutions to thermal problems of friction for three tribosystems, i.e. strip/ strip, strip /semi-space and semi-space /strip /semi-space, which simulates the process of frictional heating in the braking system. In the course of studies carried out for the commercial materials used in braking system, the influence of the proportions and evolution of thermal load, of contact surface heat conduction, and of free surfaces cooling intensity on the distribution of temperature fields and thermal stresses was investigated.

INTRODUCTION

The research results demonstrate significant influence of temperature on friction and wear of frictional nodes of contemporary machines and mechanisms. As a consequence of the temperature increase, thermomechanical properties of materials change, the processes of diffusion, as well as the oxide layers creation, are intensified, and structural changes in the surface layer occur. The phenomena mentioned induce the modifications in the manner of friction pair interaction, in other words, in its friction properties. It means, that at the stage of design and construction of various frictional nodes, as well as at friction nodes testing stage, one should be familiar with the temperature level on the contact surface, since it is usually at the highest point there. In order to obtain the information concerning the maximum temperature, it is advisable to conduct experimental survey or to exploit elaborated mathematical models, which enable to determine temperature evolution in the theory. For example, the study of temperature influence on braking time, and on the resistance to frictional components wear, too, is of a crucial importance in braking systems design.
Mathematical modelling of the heat generation process occurring during friction demands the examination of several problems, namely a thermal problem of friction (determination of temperature field and thermal stress distribution), a contact problem complying with heat generation due to friction (determination of contact pressure, size and shape of nominal contact area, and the location of actual contact areas for unrestricted time), a problem of examination of the changes in materials' properties under the influence of the temperature, and a problem of experimental or numerical verification of results obtained from theoretical inquiries. The advancement of the study and of the research of the issues mentioned is diverse. Significant success was achieved particularly in analysis of the nature of heat generation and diffusion in the process of friction, as well as in elaborating on analytical and numerical approach solving boundary-value problem of contact engineering and friction heating modelling by FEM in the system pad /disc. On the other hand, analytical approach solving the problem of frictional heat including heterogeneity of materials of the contact body, thermal resistance on the contact surface, convective heat exchange of free surfaces, and changes in sliding speed time and in contact pressure has been investigated unsatisfactorily and it is an issue to be elaborated on. The complete presentation of the development of the contemporary condition, formulating and developing of analytical-numerical methods of solving one-dimensional thermal problems of unset friction was presented in the article [1]. The information concerning methods of solution of two- and three-dimensional contact problems are included in reviews published in articles [2-4].
In this article we present and compare solutions of thermal problem of friction for three tribosystems, i.e. strip /semi-space [5-7], semi-space /strip /semi-space [8-10], and strip /strip [11].

DESCRIPTION OF ONE-DIMENSIONAL ANALYTICAL MODELS AND NUMERICAL ANALYSIS

The aim of the research was to devise effective, analytical, and analytical-numerical methods for solving thermal problems of friction of plane-parallel surface confined bodies, allowing of the change in friction power time, thermal resistance on the contact surface, convective heat exchange with the environment on free surfaces, and non-homogeneity of the materials of the frictional pair elements. In order to accomplish the objective, appropriate boundary-value heat conduction and quasi-static thermoelasticity problems for three frictional systems i.e. strip /semi-space, semi-space /strip /semi-space, and strip /strip were formulated and solved. The subject matter of the research was connected with nonstationary temperature and thermal stress fields in the aforementioned systems. The scope of the research included linear heat conduction theory for differential equations in parabolic-type partial derivatives as well as quasi-static, non-conjugate theory of thermoelasticity.
The boundary-value heat conduction problem related to frictional systems, namely strip /semi-space and semi-space /strip /semi-space with constant power density of friction force, was solved by the application of Laplace integral transform, followed by the integration of complex functions by means of Cauchy's theorem, resulting in transition to the space of the original components. The problem related to the strip /strip system was solved by means of separation of variables. On the basis of Duchamel's theorem, thermal problems of friction for the considered systems in the case of

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time-dependent density of power of friction force was obtained. The analysis of the appropriate thermal stresses was performed within the scope of S. Timoshenko model of thermal bending of thick plate with free ends [12].

The presented mathematical models of friction-related heat generation process are based on the, commonly applied in linear heat conduction and non-conjugate thermoelasticity theory, following fundamental assumptions: 1) the bodies are considered as continuous centres of the assigned physical properties which may be constant (homogeneous body) or may depend on the position of the selected point (heterogeneous body). The state of the body is to be described by means of the function of the state of the point and the time which are dependent on coordinates (e.g. temperature fields, components of the displacement vector, and the stress tensor); 2) in order to describe heat generation process resulting from friction, occurring on contact surfaces of two bodies, the model of "thermal roughness" is applied. According to the model, thermal energy generation occurs at the actual contact field, which is the sum of the fields where the vertices of the separate roughness of the friction surfaces contact. The roughness and the chemical reaction products, which fill empty spaces, cause thermal resistance in the area of their impact; 3) heat energy diffusion is taken into consideration only along normal to the contact surface, what, as established in the works of F. Ling, A.V. Chichinadze, and T. Newcomb, is reasonable as far as Peclet number ≥ 10 is concerned. It signifies, that temperature fields distribution in the frictional systems considered is the result of evaluation of parabolic type heat conduction equation with appropriate boundary value conditions; 4) the solution of the appropriate contact problems of thermoelasticity derives from thermal stress quasi-static theory. It is believed that the size of deformation of the contact surfaces is as small, in comparison with body dimensions, that boundary conditions may be recorded on the contact surface not being prone to deformation; 5) the influence of frictional surfaces on temperature and thermal stresses distribution is not taken into consideration.

Using the obtained analytical models, numerical analysis was performed for materials used for components in hard loaded systems brakes of planes, i.e.: metal-ceramics FMC-11 pad (strip), cast iron ChNMKh disc (strip or semi-space) and steel 30KhGSA calliper (semi-space) [13].The influence of duration of increase in pressure; sliding speed; heat transfer through a contact surface; convective heat exchange of free surfaces and time braking on the distribution of temperature fields and thermal stresses for such elements as disc, pad and calliper have been studied. The obtained results of contact temperature from the analytical models corresponds closely with the experimental data [13].

Additionally, we have been allowed to determine the limits of the thickness of the strips in the strip /strip tribosystem, at which the solution may be replaced with another suitable solution for the strip /semi-space or semi-space /strip /semi-space tribosystems.

CONCLUSIONS

Short-lasting processes of nonstationary frictional heating of such types of friction nodes as braking systems, can be described with high level of accuracy by means of the achieved analytical solutions, what facilitates parametric analysis performance and attainment of asymptotic temperature evaluation (i.e. qualitative and quantitative study of various input parameters influence on thermal processes occurring near the area of frictional elements contact). The results presented can have practical application in thermal calculations of the key elements of braking systems such as pad, disc, or calliper. Accordingly, they can function as a foundation to elaborate on recommendations to predict undesirable phenomena in friction nodes, such as seizure or material softening in top layers.

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