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A comprehensive approach for the simulation of heat and heat-induced phenomena in friction materials

K. Bode [1], G.-P. Ostermeyer *

Technische Universität Braunschweig, Institute of Dynamics and Vibrations, D-38106 Braunschweig, Germany

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ABSTRACT

The development of composite friction materials, such as organically bound brake pads, is to a great extent done on the basis of experience. Material developers have very few software tools available, which support the development process with simulations and help to reduce the number of prototypes and tests.

The focus of this work is on the temperature field in organic friction materials, which is associated with many friction induced effects. To understand and predict these phenomena, a discrete model is introduced, which fully considers the material's heterogeneity down to a mesoscopic scale. Heat input and heat conduction, as well as heat transfer between pad and disk, are calculated based on a finite difference method. In order to produce stable and repeatable simulation results, a special approach for the geometrical arrangement of the different material ingredients inside the considered domain is suggested.

In the context of case studies, the temperature field in a sample material is calculated for a typical stop brake application. In addition, different model extensions are discussed, which allow a spatially resolved calculation of thermally induced effects. Therewith, a comprehensive concept is presented that allows to virtually compare material variants in an early development phase. It can be easily extended with respect to further simulation tasks.

1. Introduction

In systems that aim at maximizing friction (e.g. in a clutch or a brake), the temperatures inside the components play a key role during the friction process. For such systems, many performance relevant effects on different length and time scales are known that correlate with the temperature level and/or the actual amount of heat input into the materials. In typical disk brake systems, a decrease of the friction coefficient during an increase in temperature (fading effect) is one prominent example that is usually accompanied by an increase in wear [1]. It is generally attributed to reduced material strength and thermal degradation. Hot spotting and hot banding phenomena are other examples. These effects are typically triggered by geometrical imperfections and lead to self-enforcing thermal distortions at the disk surface [1,2]. In terms of brake noise and comfort, hot spotting is in particular highly relevant, since it can lead to noticeable brake torque and car body oscillations. On the basis of experience, this phenomenon can however be influenced by pad material modifications. With their high-speed infrared thermography, Cristol-Bulthé et al. visualized that the energy dissipation between brake pad and disk is a complex, time-dependent and dynamically changing process [3].

For a discussion of friction induced temperature fields, it is worth to mention that the variable 'temperature' has a special status. On the one hand, it can be considered as an effect of the tribological process, since generally known, most of the energy in a friction system is converted into heat. On the other hand, many physical and chemical effects that change the tribological conditions, and therewith the energy dissipation, are triggered in certain temperature regimes. Thus, temperature is both, an input and output variable of the friction process, which is one reason why an understanding and prediction of friction phenomena is so challenging.

Primarily, this work focuses on disk brake systems with organically bound brake pads that are made of a mixture of different functional ingredients. These materials are manufactured by hot pressing and are most common in the automotive industry [1]. An optimization of the mixture and its tribological properties, in order to meet the requirements of the specific application, is mostly done on the basis of experience and cost-intensive testing. One reason is that material developers have very few simulation tools, which systematically support the development process. However, many of the mostly thermally induced friction phenomena can be influenced

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* Corresponding author. Tel.: +49 531 391 7000; fax: +49 531 391 7017.
E-mail addresses: kai.bode@audi.de (K. Bode), gp.ostermeyer@tu-braunschweig.de (G.-P. Ostermeyer).

[1] Present address: Audi AG, D-85045 Ingolstadt, Germany.

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by an appropriate combination of material ingredients and their properties. Thus, a precise description and simulation of thermal effects on the microscopic level has the potential that friction performance relevant phenomena can be identified, evaluated and optimized before the first prototypes are manufactured. Contributing to this overall goal is the aim of this paper.

A calculation of transient temperature fields inside friction materials is not new. For the situation of a linearly decreasing heat flux over time, which can be regarded as a brake application with constant friction conditions, Newcomb gave some analytical solutions [4,5]. Since he modeled brake pad and disk as semi-infinite plates in perfect thermal contact, his equations describe a one-dimensional flow of heat, only. Talati and Jalalifar [6] derived a similar set of equations, which is, in addition to the description of temperature versus time and depth, also able to cover convective heat transfer by the disk and a temperature gradient in radial direction. However, such analytical solutions have the major disadvantage that (with minor exceptions) they can only be derived for homogeneous materials. Thus, in particular the brake pad has to be approximated by an integral thermal conductivity and heat capacity. On the one hand, assigning just two thermal parameters to a complex composite material is a very rough approximation, when exact temperatures on the microscopic level are of interest. On the other hand, such overall parameters are generally not a-priori known, so that prototyping and measurements with the actual material composite are required. For this reason, the value of analytical solutions for a prediction of friction phenomena is limited.

With discrete models, such as finite element meshes, many more degrees of freedom are available, since almost no limitations on the geometrical complexity exist. Moreover, situations can be described, where the boundary conditions are changing over time. This is e.g. the case when an evolution of thin films modifies the tribological conditions [7] or when the surface of at least one friction partner is subject to a dynamically changing plateau–valley structure [8,9], so that the heat input is no longer evenly distributed along the contact surface and/or discontinuous in time. In a previous study related to an automotive brake, a strategy has been outlined how such dynamics can be covered during a temperature simulation [10]. A discrete model for the contact of a brake pad with a brake disk, which also covers a friction layer with individual thermal properties, can be found by Majcherczak et al. [11]. However, the authors neglect the brake pad's heterogeneity by assigning simple integral material constants to this component.

The aim of this work is to suggest a representative model of a typical automotive brake pad, which is able to fully cover its heterogeneity and therewith becomes sensitive to virtual changes of material ingredients and their properties (Section 2). With the focus on the three-dimensional temperature field inside the brake pad, appropriate boundary conditions will be introduced that also cover the thermal interaction with the brake disk. In a later part (Section 3), strategies will be shown how thermally induced friction effects can be modeled on a microscopic scale. From a measurement point of view, such phenomena are e.g. identifiable by thermogravimetry (TG), differential thermal analysis (DTA) and evolved gas analysis (EGA). Combining these laboratory tests allows the material expert to draw conclusions on thermal effects, their temperature ranges and chemical reaction rates. For a typical semi-metallic automotive brake pad, Ramousse et al. [12] have published the following data:

- 250–475 °C: decomposition of the phenolic resin binder.
- 300–475 °C and 525–700 °C: oxidation of coke (double-stage process).
- 600–850 °C: oxidation of graphite.
- 500–800 °C: oxidation of iron.

Although the actual mixture of an organic friction material is highly individual for each application, this data is roughly transferable to other pad mixtures of the same material class (semi-metallic in this case). Section 3 will show in principal, how such data can be used together with the model developed in Section 2. Therewith, a comprehensive approach is suggested, how friction material variants and their behavior during the friction process can be virtually compared and evaluated in an early development phase.

2. Friction material modeling for thermal studies

2.1. Principal model layout and mathematics

As discussed above, a discrete model is the only reasonable approach to follow the objective of this work. In order to keep the complexity manageable, only a representative fraction of the tribological system is considered. In addition, the disk curvature and therewith a radially changing sliding speed is neglected for reasons explained below. The friction material is modeled three-dimensionally, so that a heterogeneous structure with ingredients of different size and orientation can be drawn. The disk is idealized as a two-dimensional flat structure, since the temperatures inside this component are not the focus of this work. Appropriate boundary conditions will however ensure that the heat flow in axial direction is covered appropriately. The model's principal layout is depicted in Fig. 1.

For the sake of simplicity, the discrete elements are chosen to be cubic with edge length d. Their midpoints can then be considered as the nodes of a regular mesh, along which the partial

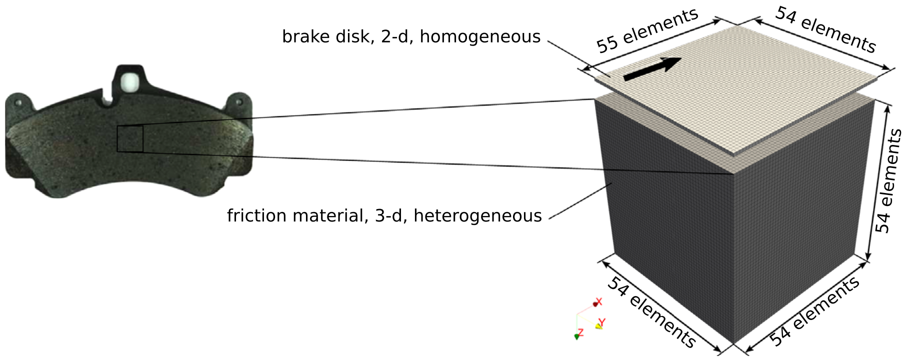

Fig. 1. Principal layout of the model with a representative three-dimensional fraction of the friction material and a two-dimensional approximation of the disk, being in thermal contact with the pad.