

Spatially Resolved Temperatures in Inhomogeneous and Continuously Changing Disk Brake Interfaces

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09/18/2011Kai Bode and Georg-Peter Ostermeyer
TU Braunschweig

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ABSTRACT

Widely known is the fact that friction and wear characteristics of disk brakes are subject to pronounced temperature dependencies. For systems with organically bound brake pads, many thermally induced material changes can occur, ranging from degassing of the phenolic resin binder up to degradation of fibers and melting of metallic components. All these effects modulate the surface structure between pad and disk. They are a major contributor to friction layer dynamics [1] and directly influence the system's performance.

Concerning the calculation of contact temperatures in disk brakes, several attempts have been made in the past. Most of them, however, use drastic assumptions (e.g. homogenous materials and ideal contact), which limit the results to qualitative approximations [2]. Recent studies already include the multi-material structure of brake pads. These give indications on how material mixtures must be changed, in order to modify contact temperatures into a certain direction [3].

This paper goes one important step further and introduces a numeric model, which is also capable to account for dynamic changes of the surface topography and chemistry during the actual friction process. It uses a new finite volume scheme for the situation of a rough pad sliding against a rotating disk, which is deduced from the problem of a point source as reference solution [4]. The algorithm can be fitted directly into existing and future cellular automata models for the friction layer dynamics [1], giving spatially resolved information on the temperature field for different surface structures. With this method, new approaches concerning the description and explicit prediction of temperature-dependent

friction phenomena are possible. Selected sample problems will be discussed.

INTRODUCTION

Modern brake pads consist of a high number of different ingredients from various material classes, in order to meet the requirement of a high and stable performance at low wear rates under different operating and ambient conditions. This diversity leads to a huge amount of possible effects during the process of friction, primarily near the contact surface, each of which influences the friction behavior on a certain time scale. Over the past years, research expertise focused on microscopic and nanoscopic surface analyses, in order to identify and classify the physical and chemical material changes [5,6].

Almost all of the mechanisms, e.g. oxidation or melting processes, are coupled to the amount of thermal energy available in the surroundings of the respective material component. Attempts to systematize the temperature-dependent mechanisms and to validate a pad's thermal stability usually include a thermal characterization of single ingredients or full brake pads by thermogravimetry (TG), differential thermal analysis (DTA) and evolved gas analysis (EGA). These laboratory tests give indications on chemical reactions and the related temperature intervals. Results for a semi-metallic brake pad and some of its components have been published in [7] and gave the following indications, which can be regarded as approximately transferable to other pad mixtures of the same material class:

- The decomposition of the phenolic resin binder is a continuous process between 250 and 475°C.
- Oxidation of coke is a double-stage process and occurs between 300 and 475°C, as well as between 525 and 700°C.
- Oxidation of graphite occurs between 600 and 850°C.

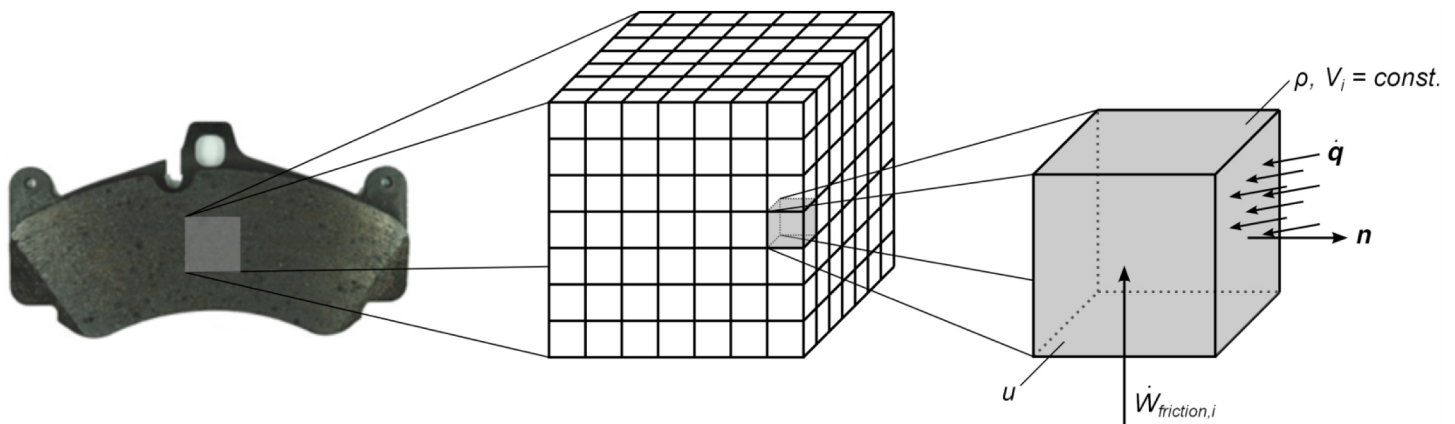


Figure 1. Discretization scheme on the basis of cubic volume elements.

- Iron is oxidized in a continuous process between 500 and 800°C.

Beyond the determination of these temperature intervals, the same laboratory equipment also allows the measurement of reaction rates, e.g. the mass loss of material per unit of time due to the process of resin binder degradation. Thus, from a measurement point of view, a description of thermally motivated friction processes with respect to time is possible. This enables a straightforward integration into novel friction models, e.g. based on the method of cellular automata [1], and an implicit description of tribochemistry without being confined to the molecular length scale, such as in MD simulations [8].

In order to meet this challenge, an accurate description of temperature and internal energy at the level of the friction boundary layer is essential. In the literature, several attempts can be found that on the one hand use the FEM for the description of brake assemblies under thermal loading [9]. These approaches give valuable information on e.g. a system's thermal distortion or durability, however, statements concerning friction effects as a result of the calculated temperatures are limited. Complex in-the-loop simulations of induced material changes with FE models have not yet been done. On the other hand, analytical descriptions of the pad-disc contact can be found that explicitly solve the PDE of heat conduction for given boundary conditions. An extensive study, which shows calculated temperature profiles for sample materials and a typical brake stop, is given in [2]. These approaches, however, use many assumptions and simplifications, such as

- homogeneity of the materials,
- a constant coefficient of friction,
- an ideal and homogeneous contact between pad and disk and
- a one-dimensional heat flux, only,

which limit the results, especially for the surface temperatures, to approximate overall values. For an in-the-

loop simulation of thermally induced tribochemistry and tribophysics, a more detailed space-resolved model is required that is also capable to account for an inhomogeneous surface and material structure that varies with time.

In the following, a heat conduction model for the friction boundary layer will be introduced, which can be directly implemented into existing friction model, as e.g. suggested in [1]. In principal, it is based on a finite volume approach that models the heat generation at the asperities as a sum of impulse functions. For the heat conduction, it uses a reference solution according to the well-known shape of the temperature field right underneath each asperity. An outlook on selected sample problems will be given at the end of the paper.

A FINITE VOLUME METHOD FOR HEAT CONDUCTION

THE FINITE VOLUME APPROACH

The discretization of the friction components into volume elements (cells), here of cubic type, is depicted in [figure 1](#) for the brake pad. On the right hand side, it shows schematically an arbitrary cell *i* together with the heat flux from its right neighbour into the volume and an external source, which is the dissipated friction power for the elements in contact with the disk. For a time step Δt , it can be written as

$$\dot{W}_{friction,i} = (1 - \beta) \mu F_{N,i} v_{rel} \quad (1)$$

with the local normal force on the element $F_{N,i}$, the relative sliding speed v_{rel} , the local coefficient of friction μ and the parameter β , which indicates the amount of dissipated energy that is absorbed by the brake disk.

In order to be thermodynamically correct, each element must follow the equations for conservation of energy. For a description of heat and temperature conduction, the balance

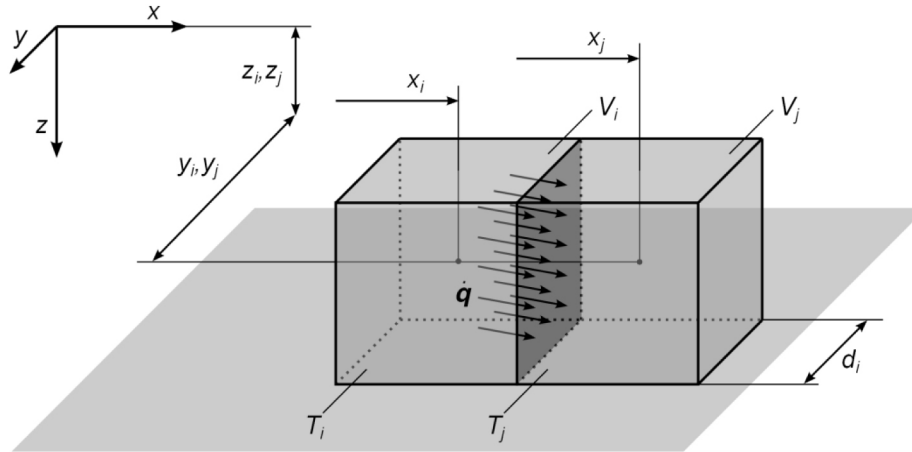


Figure 2. Heat conduction into positive x-direction between a cubic cell i and its neighbour j.

of the internal energy u is of major interest. With the specific heat capacity at constant volume

$$c_v = \frac{du}{dT} \quad (2)$$

this part of the energy directly correlates with the temperature T , when deformations of the volume element are negligible from an energetic point of view. When heat radiation and heat generation by chemical reactions are also neglected, the internal energy of the cell element in [figure 1](#) follows the balance equation:

$$\rho c_v \int_{V_i} \frac{dT}{dt} dV = - \int_{\partial V_i} \dot{q} \mathbf{n} dA + \dot{W}_{friction,i} \quad (3)$$

Since the temperature is assumed to be constant over each volume element, the integral on the left hand side can be approximated easily by a difference quotient, such as in a finite difference scheme. The right hand side of [equation \(3\)](#) includes the heat generation according to [equation \(1\)](#) and a surface integral that covers the heat conduction to or from the adjacent cells. For a cubic element, it is a sum over all the six side faces. In the following, the surface integral will be discussed for the side face that points into positive x-direction ([figure 2](#)), which is shared with a neighbor cell j. Due to symmetry, the algorithm developed with this side surface is in the same way valid for all the other cell-cell interactions.

Applying Fourier's law of heat conduction

$$\dot{q} = -\lambda \nabla T \quad (4)$$

to [equation \(3\)](#), the thermal interaction between cell i and j ([figure 2](#)) can be written as

$$\begin{aligned} \frac{T_{i,t+\Delta t} - T_{i,t}}{\Delta t} \bigg|_{x_i + \frac{d_i}{2}} = \\ \frac{\kappa}{V_i} \int_{z_i - \frac{d_i}{2}}^{z_i + \frac{d_i}{2}} \int_{y_i - \frac{d_i}{2}}^{y_i + \frac{d_i}{2}} \frac{\partial T}{\partial x} \left(x_i + \frac{d_i}{2}, y, z, t \right) dy dz \end{aligned} \quad (5)$$

with $\kappa = \lambda/(\rho c_v)$ being the thermal diffusivity that summarizes the thermophysical material properties. In order to be able to use this equation as an update rule over each time step Δt , the surface integral must be solved or at least adequately approximated.

A REFERENCE SOLUTION FOR FRICTION COUPLES

The surface integral in [equation \(5\)](#) can be tabulated easily, when the structure of the temperature field in which cells i and j reside is known a-priori. This is not necessarily the case for any arbitrary problem of heat transfer. However, for the configuration of two solid bodies sliding against each other, such an approach is possible. The key point is that frictional contact and heat generation occur at numerous asperities and contact plateaus, which are highly fragmented and much smaller than the nominal contact area of e.g. a typical brake pad and the disk.

With respect to thermal modeling, these zones can be regarded as point-shaped heat sources that emit energy into the bulk material, which in comparison is infinitely large. The temperature field induced by each point source is hemispherical in the vicinity of the surface. [Figure 3](#) shows this interpretation schematically for a measured pad topography.