

Thermal Effects in Friction Materials - A Comprehensive Strategy for Modeling and Simulation

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ABSTRACT

Shorter product cycles, a high awareness for comfort properties on the customer side and an increasingly strict legislation with respect to environmental issues make the development of friction materials more and more challenging. In contrast to many other engineering tasks, nearly no software tools are available to the material developer, which systematically support the development process with simulations.

This work focuses on the time-dependent three-dimensional heat distribution inside a pad material and shows, how heterogeneous material mixtures can be modeled, such that a prediction of non-stationary temperature fields becomes possible. In this context, a strategy is suggested, how the thermal interaction between pad and disk and the aspects of energy dissipation and heat partitioning can be described appropriately.

The outcome is a simulation system that not only returns local temperature values for arbitrary boundary conditions, but which also makes a prediction of heat-induced physical and chemical phenomena possible, as they occur inside the material. Different case studies show how e.g. the oxidation of certain components or the degassing of the organic binder can be described. These concepts allow the material developer to systematically and virtually compare material variants in the early stage of a development process and to reduce the need for extensive prototyping and testing.

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INTRODUCTION

Friction and wear, as well as numerous comfort aspects of today's vehicle brake systems, are correlated with the temperature level in brake pad and disk. Most prominent are hot judder phenomena, caused by hot spots and thermal distortions near the disk surface, as well as the fading effect. An appropriate choice or modification of the friction material can significantly influence many of these critical effects. Thus, a precise prediction of heat-induced phenomena inside a material will also allow important conclusions on its friction and wear characteristics. Until today, material selection and optimization are, however, mostly done on the basis of experience. The reason is that material developers have very few simulation tools to systematically support the development process. However, extensive prototyping and testing is cost-intensive, which motivates the development of new simulation strategies for the complex, heterogeneous friction materials.

A calculation of temperatures inside the friction components during braking is not new. First analytical solutions, which describe brake pad and disk as semi-infinite plates in perfect thermal contact, were formulated by

Newcomb [1,2]. These consider a linearly decreasing heat flux in the contact interface and allow a description of temperature as a function of depth. A relatively new but in principal similar set of equations was published by Talati and Jalalifar [3]. However, analytical solutions have their limitations: They can only be derived for homogeneous materials, which leads to the conflict that an organically bound brake pad must be described by an integral thermal conductivity and heat capacity. These values, however, are mostly not a-priori known and must be measured using the actual material composite. This leads to the conflict that a thermal simulation of material variants cannot be done before prototyping, so that the benefit of simple analytical solutions to the material developer is limited.

Discrete models, on the other hand, have the potential to also cover complex structural aspects. They allow a thermal description of almost arbitrary geometries and can describe contact situations, where the heat input is not evenly distributed, e.g. due to a dynamically changing plateau-valley structure of the friction surface [4,5]. In addition, numerical models can easily handle boundary conditions that are not constant over time. With respect to friction, this even allows

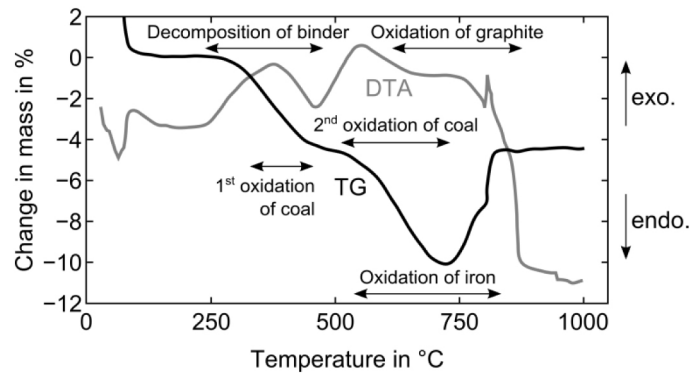


Figure 1. Thermogravimetric (TG/DTA) analysis of a semi-metallic friction material, revealing typical thermally induced effects and their temperature ranges (redrawn after [7]).

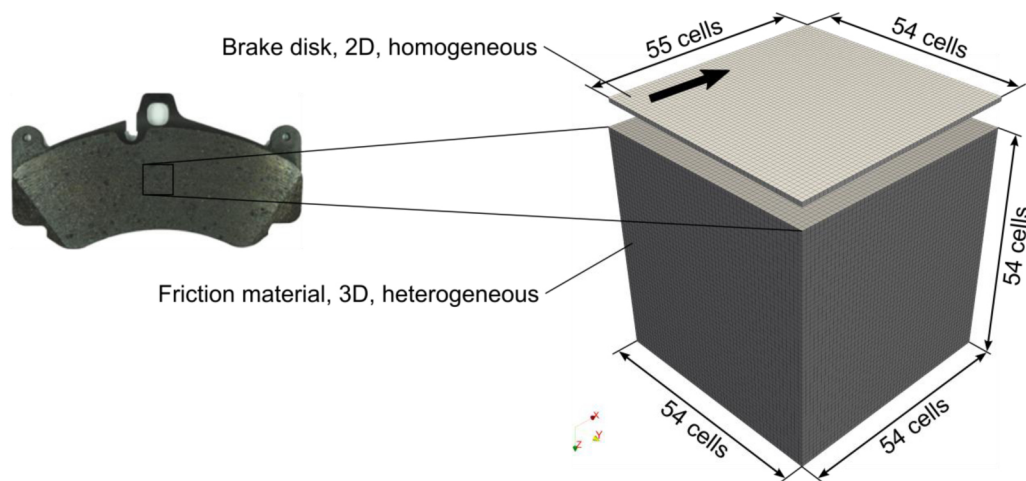


Figure 2. Model structure with the “material unit cube” as a three-dimensional, representative section of the brake pad material.

to describe situations with a highly transient heat input, e.g. due to changes in friction properties and/or sliding speed. A discrete model of the friction partners in a brake system, which also covers a friction layer between pad and disk, can be found by Majcherczak et al. [6]. However, this model also neglects the brake pad's heterogeneity and describes heat and temperature conduction by means of simple integral material constants.

The aim of this work is to show an approach for a thermal friction material simulation, which is sensitive to the material mixture and the individual ingredients used. Therefore, a three-dimensional material model will be introduced, together with appropriate boundary conditions that cover the thermal interaction with the disk. The model developed will not only allow an analysis of time-dependent temperature profiles, but will be parameterized in order to predict heat-induced effects inside the pad as those depicted in [Figure 1](#). This data plot shows the mass loss of a typical semi-metallic pad material (TG signal) during heating up to a level of 1000°C. Together with information on the energy absorbed or emitted by the sample (DTA signal), the material expert can draw

conclusions on thermal effects inside the material. With such data and the model developed in the following, a comprehensive strategy is suggested to the material developer, which allows a virtual comparison of material variants in an early product development stage.

FRICITION MATERIAL MODELING

Model Structure

For the reasons mentioned above, the material modeling is based on a discretization of the components into a grid of cubic elements ([Figure 2](#)). Along this grid, the heat conduction is solved numerically by difference equations, as e.g. discussed in the context of brake friction in previous work [8].

In a simple explicit form, the temperature change inside an element (i,j,k) due to the heat exchange with an adjacent element ($i+1,j,k$) during the time step Δt can be written as

Table 1. Sample friction material formulation and number of elements required for each ingredient to represent the exact volumetric content (in a 54×54×54 elements grid).

Ingredient	Volumetric content	Corresponding # of elements	Shape / average size	Representation in model
Coke	17,5	27840	Particle / ≈ 500	30 particles, 928 elements each
Granulate material	14,0	22272	Particle / $\approx 500 \mu\text{m}$	24 particles, 928 elements each
Steel fiber	7,0	11024	Fiber / $\approx 50 \mu\text{m} \times 180 \mu\text{m}$	2756 fibers, 4 elements each
Aluminum oxide	3,5	5511	Particle / $\approx 25 \mu\text{m}$	Single elements, stochastic
Tin sulfide	3,5	5511	Particle / $\approx 50 \mu\text{m}$	Single elements, stochastic
Magnesium oxide	14,0	22045	Particle / $\approx 50 \mu\text{m}$	Single elements, stochastic
Phenolic resin	10,5	16534	Binder / –	Single elements, stochastic
Air	30,0	46727	Pore / –	Single elements, stochastic
Sum	100,0	157464		

$$(T_{i,j,k}^{t+\Delta t} - T_{i,j,k}^t) = \frac{\tilde{\lambda}_{M1,M2}}{d^2(\rho c_v)_{M1}} (T_{i+1,j,k}^t - T_{i,j,k}^t) \cdot \Delta t. \quad (1)$$

Therein, ρ and c_v are density and specific heat capacity. In addition, the indices $M1$ and $M2$ denote the different materials of element (i,j,k) and $(i+1,j,k)$, respectively. If their thermal properties are different, $\tilde{\lambda}_{M1,M2}$ comprises the individual thermal conductivities λ_{M1} and λ_{M2} , as well as a thermal contact resistance R_C , which accounts for the fact that the thermal contact between elements of different materials is not perfect (phase boundary):

$$\frac{1}{\tilde{\lambda}_{M1,M2}} = \frac{1}{2} \left(\frac{1}{\lambda_{M1}} + \frac{1}{\lambda_{M2}} \right) + R_C d. \quad (2)$$

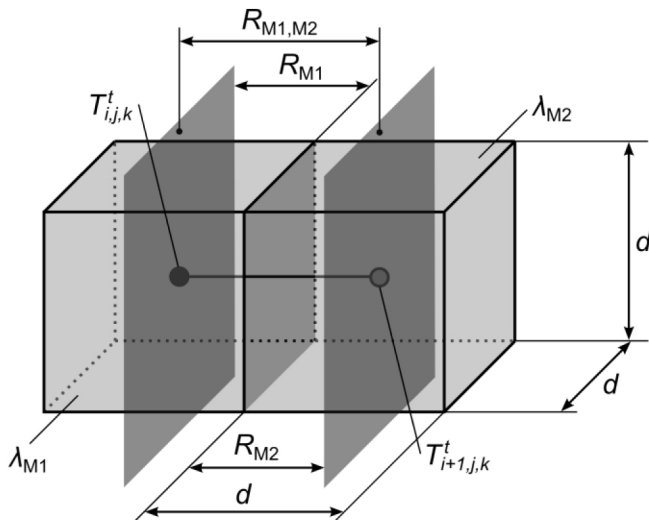


Figure 3. Two adjacent elements in the discrete model with different material properties $M1$ and $M2$.

Equation (2) can be derived, when the two halves of the adjacent elements that contribute to $\tilde{\lambda}_{M1,M2}$ are considered as

thermal resistors R_{M1} and R_{M2} connected in series (Figure 3), with

$$R_{M1} = \frac{d/2}{\lambda_{M1} d^2}. \quad (3)$$

for Material 1 and an analogous expression for R_{M2} .

The “Material Unit Cube”

To appropriately cover the pad material's heterogeneity, an approach is suggested, which follows the concept of a “unit cube”, similar to the unit cell of e.g. a metallic structure. Therefore, the term “unit cube” will be used in the following as a synonym for the friction material model depicted in Figure 2. The unit cube shall have an edge length of 2.7 mm with an element size of $50 \mu\text{m}$, giving an array of $54 \times 54 \times 54$ elements (Figure 2). These dimensions are large enough to generate a model that is representative for the mixture given in Table 1, i.e., the edge length exceeds the largest particle diameter by a factor of more than 5. Smaller particles can be modeled down to a diameter of $50 \mu\text{m}$, identical to the element size. Ingredients that are even smaller (e.g. aluminum oxide, see Table 1) are inevitably considered as agglomerates of $50 \mu\text{m}$. This is however acceptable, since such agglomerates also occur in reality. Moreover, a refinement of the discretization would disproportionately increase computational time, since the square of the element length d also determines numerical stability. Thus, a smaller d not only causes more elements that need to be calculated, but in addition, very small time steps are required.

In order to be representative, the unit cube must be filled with material data according to the brake pad formulation considered. This not only requires a precise implementation of the ingredients' thermal properties, but also an exact representation of their volumetric content. Table 1 lists a sample pad composition that will be used in this work for an illustration of the modeling concept.

One possibility to virtually “fill” the cubic model with these different materials, taking account of the number of elements per ingredient and the varying particle size, is a