

Modeling of Friction Evolution and Assessment of Impacts on Vibration Excitation at the Pad-Disc Interface

W. Österle and H. Klobß

Federal Institute for Materials Research and Testing (BAM)

A. I. Dmitriev

Institute of Strength Physics and Materials Science

Copyright © 2008 SAE International

ABSTRACT

The frictional behaviour at the pad-disc interface has been simulated on the nanometer scale with the aid of the method of Movable Cellular Automata (MCA). The boundary conditions of the model were adjusted to experimental observations obtained by Transmission Electron Microscopy (TEM) showing that friction layers are mixtures of nanocrystalline iron oxide with a solid lubricant. A major benefit of this kind of modelling is that the impact of composition, pressure and velocity changes not only on the mean Coefficient of Friction (CoF), but also on CoF-fluctuations during the sliding simulation can be studied. Thus it has been shown that only under certain conditions, when a Mechanically Mixed Layer (MML) had formed, the CoF was stabilized with a minimum of fluctuations. On the other hand, when the MML was not formed, a stick-slip type of sliding occurred which was accompanied by damage of the interface layers. The remaining metal-on-metal or oxide-on-oxide contacts show higher CoF-values. Thus we conclude that the occurrence of high frequency vibrations during braking might be related to local degradation of the friction layers leading to unstable and locally differing CoF-values.

INTRODUCTION

According to S. K. Rhee, the excitation of high frequency squeal during braking occurs at the pad-disc interface where the pad adopts the function of a microphone and the disc the function of a speaker [1]. In fact, many different parameters like friction level, damping, stiffness, surface roughness, humidity and, last but not least, mode coupling between natural frequencies of the different parts of the brake system may contribute to the NVH (Noise-Vibration-Harshness) issue. Our intention was not to discuss methodologies for solving NVH problems, which are described in the literature e.g. [1, 4]. We focused on the first point of the above list and tried to find answers to the following questions: i) Which micro-mechanisms are capable to increase the friction

level and thus eventually may lead to NVH problems, and ii) what could be the reason for this frequently observed behaviour? Since single excitation events correspond to localized features at the pad-disc-interface, it is useful to regard micro-contacts and to elaborate the range of differences which can be expected.

A third body with different properties than the two first bodies at the interface of a tribological couple was suggested earlier by Godet [2] and predicted for brake materials by Jacko et al. [3]. Whereas mechanical engineers often regard the third body hypothetically as a viscous film, material scientists observe material changes which they have termed friction layers or friction films. Although friction film formation has been identified to play an important role in brake squeal, it is not clear yet how to incorporate complex tribological processes into predictive models [4]. An experimental observation, which has been confirmed many times is, that noise propensity increases with increasing CoF [4-6]. The theory of friction-induced self-excited vibration also predicts an increase of squeal propensity with increasing CoF [4]. Rhee et al. [6] related the occurrence of squeal to friction film formation and a corresponding increase of the CoF, but this relationship seems not to hold generally. It is well known in practice, that steel-free NAO pads show lower CoF-values and noise propensity than low-met pads despite of much more pronounced film formation of the former compared to the latter. Therefore it is important to regard the structure of friction films and the possible impact of structural changes on film properties.

Our approach to obtain a feeling of the frictional behaviour at the pad-disc interface has been modeling on the nanometer scale with the aid of the method of Movable Cellular Automata (MCA), which was developed by Professor Psakhie's group in Tomsk [7]. The boundary conditions of the model were adjusted to experimental observations obtained by Transmission Electron Microscopy (TEM) showing that friction layers are mixtures of nanocrystalline iron oxide with a solid lubricant as for example graphite [8]. In the following we intend to show that many features of frictional behaviour

can be explained referring to the structure of surface films and locally different contact situations.

CHARACTERIZATION OF FRICTION LAYERS

EXPERIMENTAL OBSERVATIONS

The commercial pad materials used in our previous studies were typical low-met pads for automotive application in Europe. Details of formulation, as far as communicated by the manufacturer, are shown in Table 1. The major metallic ingredient are steel fibers, besides brass and copper chips. Aramid fibers have been used as substitute for asbestos. Solid lubricants comprise mixtures of MoS₂ and Sb₂S₃ or MoS₂, FeS and SnS. Carbon (C) corresponds to coke particles which are partly amorphous but also contain graphite micro-crystals. Fillers are mainly silicates, but also abrasive particles e.g. chromite and corundum which adopt the function of removing transfer films from the cast iron brake disc and polishing the surface, respectively.

Table 1 Formulation of pad materials in mass %

Rubber	Resin	Fibers	Metals	Fillers	Solid lub.	Carbon
1-2	7	2-3	38-39	20-23	13-18	12-15

During braking cycles surface temperatures can readily reach 300°C or more which leads to decomposition of the resin and release of particles from the pad surface. All particles, except the abrasives, are crushed to pieces, and furthermore, tribo-oxidation of steel fibers and the cast iron disc provides iron oxides to the wear debris. As a consequence, the wear debris contains all ingredients of the pad formulation mixed on a very fine scale (nanocrystalline microstructure), and its major constituent is iron oxide, corroborating the fact that iron is the major constituent of both, pad and disc. Signs of the scenario described above have been observed very frequently in all our previous work, as summarized in [8] and also by other colleagues e.g. [3, 5, 9-13].

The wear debris is not only ejected out of the contact in the form of brake dust, but part of it remains at the pad-disc interface and forms friction layers. Fig.1 shows a cross-section through such a layer, demonstrating how thin such layers usually are. The micro cross-section was prepared and imaged by Focused Ion Beam (FIB).

Friction layers like the one shown in Fig.1 (composition given in Fig.9) were always observed after an appropriate bedding procedure and under moderate braking conditions i.e. if the surface temperature of the disc did not exceed 300°C. The test conditions were comparable to the standard test procedure SAE 2522 (AK master), but without fading cycles.

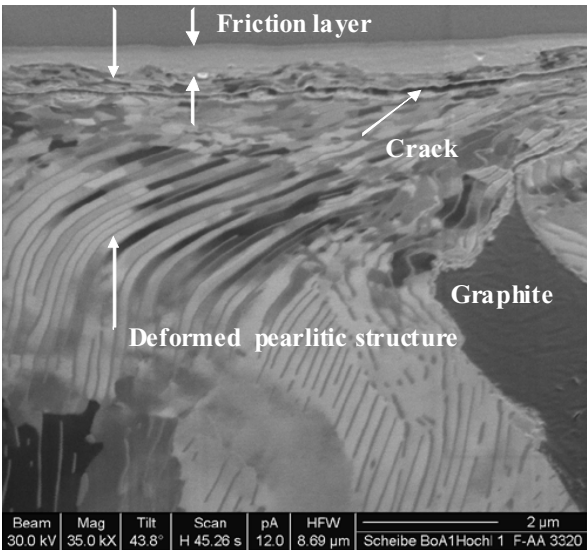


Fig.1 Cross-section of friction layer on brake disc

MODELING

Although the principles of MCA-modeling have been described in our previous papers [8, 14, 15], the following paragraph will recapitulate the basic considerations: The region of interest to be simulated is the interface between pad and disc where friction and wear takes place. Velocity accommodation between the stationary pad and the rotating disc can be accomplished by assuming a flow of granular wear debris (3rd body) in the gap between the two 1st bodies. Observation of the friction layer (Fig.1) and its structure [8] imply that the granular particles must be very small, i.e. of the order of 10 nm in diameter. The friction layers on both 1st bodies might be interpreted as sintered layers of wear debris, formed after milling and mechanical mixing of larger wear particles. In the model the particles correspond to interacting elements of finite size (10 nm) which are linked to each other within the friction layers. The bonding state can be switched from linked to unlinked and vice versa depending on contact stress and inter-particle distance, respectively. Thus it is possible to simulate not only asperity deformation, wear mechanisms, mechanical mixing, detachment of particles and granular flow, but also the recombination of particles, e.g. welding of metallic particles.

The different materials involved in 3rd body formation enter the model by attributing their stress-strain characteristics to individual automata. Since in reality the situation is very complex, some simplifications had to be introduced, as shown schematically in Fig.2.

Actually, we regard only one very small contact in two dimensions defining a micron-sized cross-section similar to the one shown in Fig.1, but comprising both sides of the interface i.e. pad and disc. On the pad side we assume a primary contact site according to Eriksson et al. [11] which is provided by a section of one of the steel fibers used in low-met pads as reinforcing elements. The supporting material on the disc side is pearlitic steel which is the matrix of cast iron. Since the regarded contact is so small, it makes no sense to use the properties of cast iron which is a composite material of

coarse graphite lamellae in a pearlitic matrix, as shown in Fig.1. The friction layer is modeled with a random distribution of single graphite particles in a matrix of iron oxide. Graphite was chosen as a representative of any other solid lubricant because its mechanical properties are well known. The mechanical properties of the different bulk materials (see table 1 in [14]) were allocated to each element (particle) in the model. Whereas the stress-strain characteristics of plastically deformed ferritic steel, pearlitic steel and graphite are well known, the mechanical properties of the iron oxide matrix of the friction layer are not known. Therefore some trials were performed assuming brittle oxides of different strength. Finally the assumption of a rather soft oxide yielded the most realistic results.

RESULTS

IMPACT OF SOLID LUBRICANT CONCENTRATION

It is quite clear that increasing the concentration of the solid lubricant in the friction layer should reduce the CoF. This expected behavior has been corroborated by the modeling results shown in Fig.3. For the layer with 27.5 % graphite (Fig.3a) the mean CoF stabilizes at a value of 0.3 after a short running-in period, whereas for the layer with only 5.5 % graphite (Fig.3b) the mean CoF increases gradually with time exceeding 0.5 at the end of the simulation. Furthermore, CoF-fluctuations between successive time steps are very different for the two situations, implying different conditions at the sliding interface.

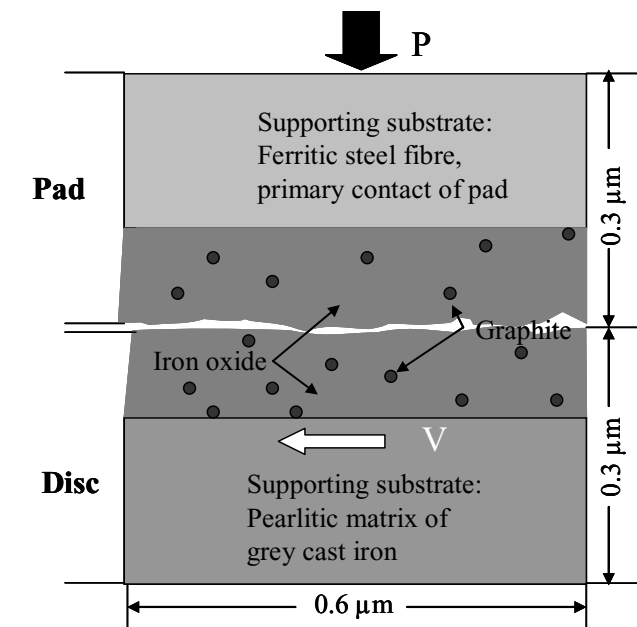


Fig.2 Schematic of pad-disc interface

Further boundary conditions for modeling besides an uniform automata size of 10 nm were: a constant sliding velocity $V = 10$ m/s, a constant pressure P in the range 5-50 MPa and periodic boundary conditions i.e. material ejected at one side is reintroduced at the other side. The time step for simulation is determined by automata size and elastic modulus. It is 10^{-13} s, similar as in molecular dynamics (10^{-15} s). Since the time step was such small, temperature changes were neglected. In principle, temperature could be introduced into the model by taking account of the temperature-dependence of mechanical properties.

A surface profile with roughness on the nanometer scale was set deliberately prior to simulation.

The model calculates position and binding state of each automaton (particle) as well as resulting tangential forces at the micro-contact for each time step.

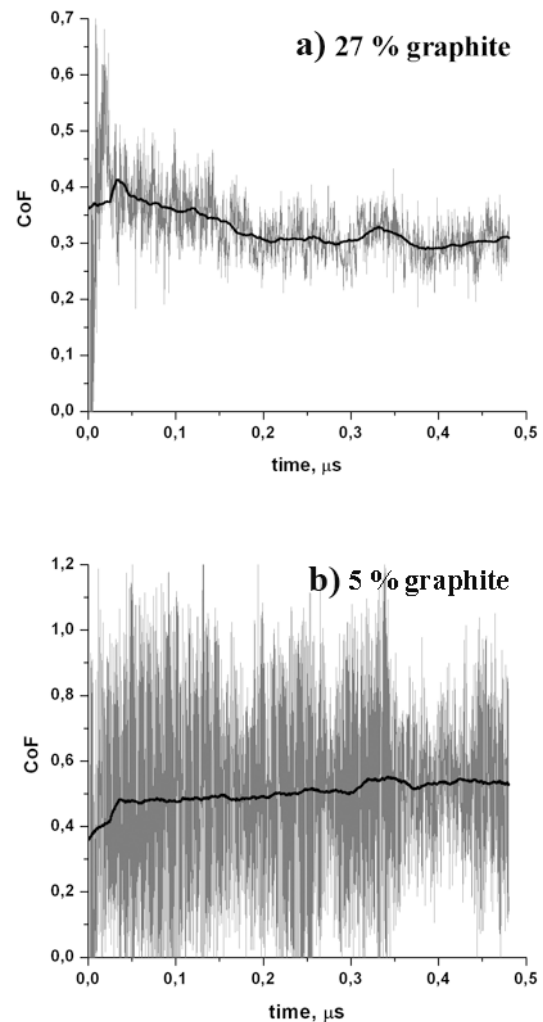


Fig.3 Simulation of CoF-evolution for two graphite concentrations at a pressure of $P = 35$ MPa

This assumption has been confirmed by regarding position and bonding state of the automata after the simulations. Fig.4a shows the situation for case 1 (high graphite concentration). A layer of particles with broken bonds and mixing of particles from pad and disc – therefore termed mechanically mixed layer (MML) – is displayed at the pad-disc interface (marked by arrows).