

Some Considerations on the Role of Third Bodies during Automotive Braking

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ABSTRACT

Third bodies, also termed friction layers, tribofilms or secondary contact patches, are layers of more or less compacted wear debris between pads and rotor of a disc brake. Our approach of assessing the sliding behavior and friction properties induced by third bodies has been: i) structural characterization after AK-master test procedure, ii) sliding simulation of model structures similar to the observed ones but with simpler and well defined compositions, and iii) verification of simulation results by pin-on-disc tests with artificial third bodies showing the same microstructures and compositions as the model structures. The idea was to simulate structure formation during real braking conditions by high energy ball milling of appropriate powder blends. The final outcome of numerous parameter studies was that a third body containing 15 vol% soft ingredients and 0-20 vol % hard ingredients, both distributed homogeneously in a nanocrystalline iron oxide matrix, should be most desirable for braking. This general description of the optimum third body structure and several parameter studies performed by modelling enabled us to interpret a number of features of the AK-master test procedure, such as i) friction evolution during bedding, ii) the role of solid lubricants in respect to the initiation of smooth sliding behavior, and iii) friction evolution during a single braking event (in-stop behavior).

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INTRODUCTION

The term "third body" was created by Godet to describe the special interface situation generally occurring during dry sliding applications [1]. Nowadays, modelling of third body behavior is widely applied using discrete element methods (DEM) [2, 3, 4] and the movable cellular automata method (MCA) [5, 6, 7, 8, 9, 10, 11]. The former method allows one to simulate particle flow and the latter combines strain and stress state modelling with granular flow modelling by introducing a switching parameter which defines whether two particles are linked or unlinked. The third body differs in structure composition and properties from the two first bodies, pad and disc in our case. Probably, Jacko et al. were the first pointing out that third body layers may play an important role during braking [12]. Furthermore, several research groups in Berlin, Uppsala and Braunschweig have discussed the role of patches formed from third body material in respect to brake performance properties [13, 14, 15, 16, 17]. Those authors pointed out that the compaction of wear debris against primary contact sites like e.g. steel fibres leads to a continuously changing pattern of secondary contact sites. Changes of macroscopic friction were related to changes of the real contact area, whereas constant friction was related to a dynamic equilibrium of contact patch creation and patch

destruction. Experimental evidence of wear particle flow and the formation and destruction of secondary patches was provided by in-situ observations during pad-on-glass tests [18]. Ostermeyer et al. used a cellular automata method to simulate possible patch dynamics during several braking situations [17]. Except the assumption of different primary contact sites like steel fibres or quartz particles, the approaches based on patch dynamics did not consider the complicated composition and structure of the third body patches. This is the point where our own research work has been focusing on. Ten years ago we have reported on the structure of so-called friction layers formed during dynamometer testing of commercial brake systems [19]. In the meantime our knowledge has increased considerably mainly by application of numerical modelling which enabled us to obtain an understanding of the sliding mechanism of nanostructured third bodies at the interface between the rotating brake disk and fixed pad. The objective of this paper was, to provide a review of the most important results of our research during the last decade, and to show how the role of the third body can be assessed by both experimental and modelling approaches. Furthermore, it will be shown that it is necessary to link patch dynamics and the

knowledge of third body sliding mechanisms in order to interpret some important features of the friction performance known from real brake systems.

EXPERIMENTAL AND MODELLING RESULTS

Types of Third Body Deposits

It has been shown in many previous papers [9,19, 20, 21] that the structure of a third body formed during braking consists mainly of nanocrystalline iron oxide, Fe_3O_4 mixed with all available species from the pad formulation on a nanoscopic scale. Mostly, patches of well adhering tribofilms were investigated by transmission electron microscopy (TEM) after the preparation of thin cross-sections with a focused ion beam instrument (FIB). The frequent mention of compacted patches in the literature suggests that these features are very prominent at the pad surface or even may cover the whole disc surface continuously. Although this may be due for some NAO pads at moderate braking conditions, it does not apply for the majority of cases, especially not for the pads developed for the European automotive market. This can be checked easily by regarding the surface of frequently used brake discs. They usually show a shiny polished appearance. If there were a continuous oxide film, although as thin as some tens of nanometers, this could be seen by color. A similar statement applies for the pad surface. Nicely displayed patches revealed by scanning electron microscopy (SEM) are frequently shown in the literature, but in reality they are rather rare events. On the other hand, everybody can grab third body material just by touching the surface of a used brake pad. It is the black brake dust covering not only the pads but also the wheels. This means that the major part of the third body is trapped at the pad surface as more or less loosely adhering powder particles. Only a small fraction consists of well-adhering compact patches, at least when regarding the surfaces after braking. Preferential sites for the deposition of third body particles are wear troughs at the pad surface as shown in [Figure 1](#).

A typical FIB cross-section showing a layer of more or less loosely bound third body particles at a pad surface is displayed in [Figure 2](#). Preferential sites for the deposition of third body at the surface of a ceramic brake disc are funnel-shaped cracks, as shown in [20]. An experiment performed in 2008 [21] revealed that there is more third body trapped at the interface if the pad is still pressed against the disc compared to the situation after the braking event, when the pad has already been released. This means that third body is continuously formed during braking, but since it does not adhere well to first body surfaces, most of it will be released after braking. In other words, the contact area provided by third body particles increases continuously during a brake stop, but after the braking event, the original contact situation is restored. This may explain repeatability of the in-stop behavior during an AK-master test after the initial bedding procedure.

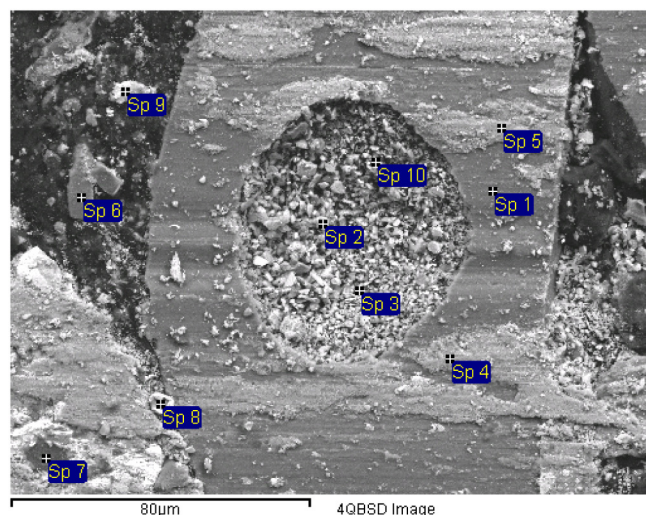


Figure 1. SEM-micrograph of a pad surface after AK-master test procedure. Loose wear particles and compact films are visible at sites Sp2, Sp3 and Sp4, Sp5, respectively. EDS of the other sites correspond to some individual ingredients of the pad formulation.

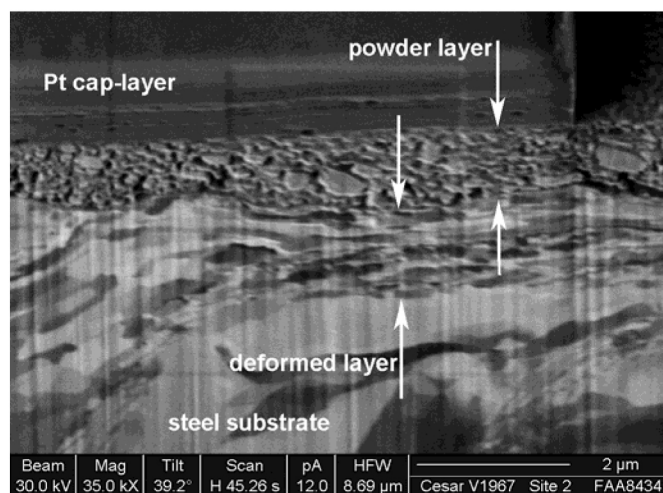


Figure 2. FIB-micrograph of a micron-sized cross-section showing a layer of partly compacted and loose particles on top of a steel fiber of a brake pad.

Modelling of Third Body Properties

Sliding Simulation of Third Body Films

The model of movable cellular automata (MCA) was applied to simulate sliding within third body films adhering firmly to both first body surfaces. The principles of this model and its adaption to iron oxide based tribofilms have been described in previous papers [5, 6]. In the following the most essential results will be reviewed and discussed in respect to their meaning for brake performance properties. Since the composition of real third bodies is very complicated, reflecting the multi-component approach of commercial brake pad formulations, it was necessary to simplify the structure for modeling.

Sliding Simulation of a Graphite Film

The most simple third body, we can think of, is a film of graphite. Graphite is always available at the disc side in form of lamella of the cast iron microstructure and it is also a frequently used pad ingredient. Since it is a soft material it is reasonable that it will wear first and thus graphite layers may form at first body surfaces. The result of a sliding simulation of graphite-based third body layers supported by steel substrates was considered in [7]. An example is shown in Figure 3.

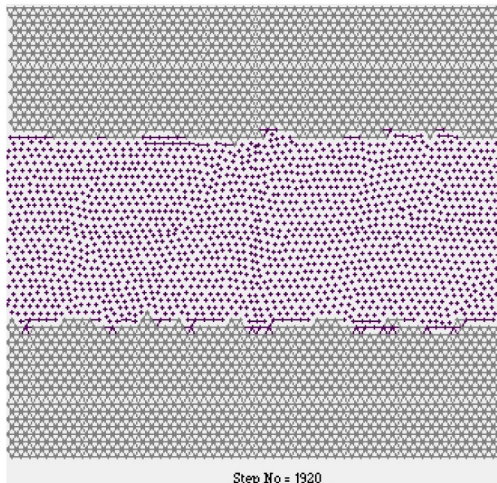


Figure 3. 2-dimensional model of a cross-section $0.5 \times 0.5 \mu\text{m}^2$ of steel substrates covered with graphite layers after sliding simulation of the lower part against the upper one. All graphite particles (magenta) are unlinked, and thus can move freely, whereas the steel particles (grey) are still linked to their neighbors.

Before sliding simulation the particles representing units of the different materials are linked, as shown by connecting lines. At the end of the simulation (Figure 3) a layer of unlinked particles is visible at the interface. This layer is termed the mechanically mixed layer (MML). Viewing the simulation in form of a movie shows a velocity gradient of moving particles within the MML. In one of our previous papers particle velocities are shown as velocity vectors [5]. This velocity gradient within the MML is very important because it provides smooth velocity accommodation between the fixed pad and rotating disc. Actually, sliding is restricted to this very thin layer of unlinked particles whereas the substrates are not affected.

Sliding Simulation of an Iron Oxide Film

A further very simple option for a simplified third body is a pure oxide film. This is reasonable because it was observed that the major constituent of the third body observed after bedding is Fe_3O_4 . A completely different sliding behavior was simulated in that case, as shown in Figure 4.

No MML was formed during the sliding simulation. This leads to a stick-slip kind of sliding without any zone of velocity accommodation. Furthermore, crack-like features occur which show that damage mechanisms are no longer restricted to a narrow zone at the interface, but may penetrate into the bulk.

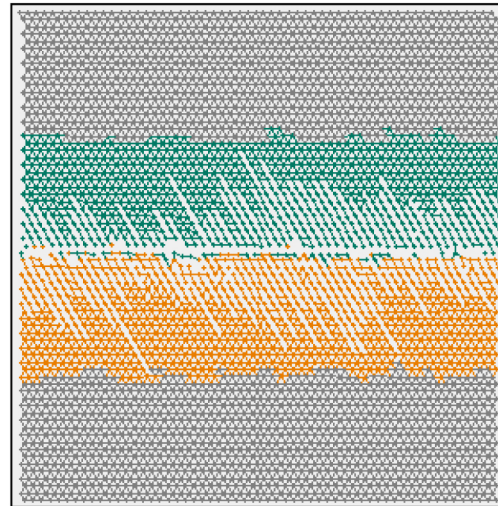


Figure 4. Structure formation during sliding simulation of pure oxide films screening steel substrates (grey). The upper oxide is shown in green, and the lower one in orange, although mechanical properties are identical.

Sliding Simulation of Oxide Film with Graphite Inclusions

A further step towards the real third body structure was the incorporation of a solid lubricant into the oxide layer. A corresponding sliding simulation is shown in Figure 5. It should be mentioned here that the upper and lower oxide were marked with different colors, although the assumed properties were the same. This was done to demonstrate mixing of material from both sides within the MML during the sliding simulation. The important feature of Figure 5 is that a MML was formed similar as for pure graphite layers and in contrast to the pure oxide layers.

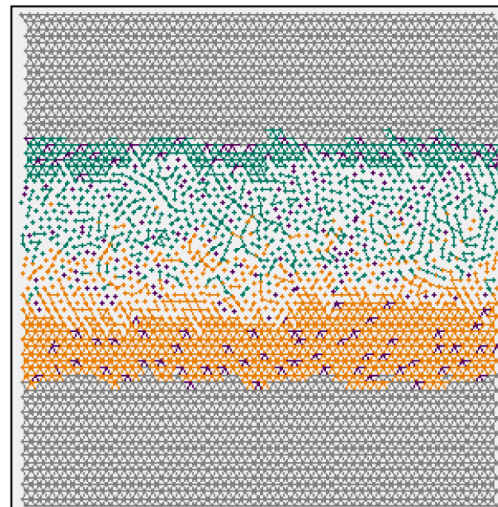


Figure 5. Structure formation during sliding simulation of the binary blend comprising of $\text{Fe}_3\text{O}_4 + 13\%$ graphite (violet). Note that upper and lower oxide are mixed at the interface and most links are broken within this mechanically mixed layer (MML).