

On Tangential Friction Induced Vibrations in Brake Systems

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ABSTRACT

The basis for the analysis of friction in brake systems is the brake pad's tribological interface. An investigation of this interface reveals friction intensive surface structures, so-called 'patches'. Their development is determined by an equilibrium of flow, which depends on the loading of the brake pad and which allows extensive insights into friction dynamics, wear behavior and heat generation. All of these aspects are mostly influenced by the varying size of the patches over time. This paper deals with a detailed analysis of the lateral vibrational dynamics of these patches on a very fast timescale. This timescale is so small that processes of patch growth and destruction are negligible. Beyond that, the vibration frequencies of the patches, as well as the actual local friction power on each of these surface structures, vary over a wide range of values, which is the result of a great variety of patch sizes and heights in the interface. Generally, one would expect a smoothing of these local and stochastically distributed vibration effects. It can however be shown, that the oscillations of the patches are subject to synchronization processes, with the result being in-phase patch vibrations on macroscopic areas of the brake pad of significant size. Thereby, self-excited vibrations of the patches can lead to lateral oscillations of the pad's friction force on a macroscopic scale. These are able to excite the whole system of brake pad and disk.

INTRODUCTION

The overall goal of brake manufacturers is the development of systems which provide a high friction force, in combination with low wear rates and inoffensive vibration characteristics. To a great extent, these aspects are determined by the tribological interface of the brake pad. This interface is characterized by a highly complex interaction of quite different phenomena from the research areas of mechanics, thermodynamics and tribo-chemistry.

Generally, research on brake system dynamics makes use of very different macroscopic models. These are in particular finite element models [1], multi-body systems [2], as well as hybrid models of beams and plates [3]. All of these are very successfully used for the analysis of

characteristic vibration modes, which are excited during typical vibration situations, such as squealing or judder. Especially for the case of squealing, it has been discovered that under certain conditions, lateral and normal movements of the brake pad can couple with bending modes of the brake disk [4], [5], [6]. The origin of lateral pad oscillations is usually described by macroscopic self-excited oscillations of the pad caused by a macroscopic decreasing friction characteristic or synthetic oscillators in the pad surface.

But this cannot explain, why sometimes there occurs squealing and sometimes not, although all load and material parameters of the brake process are the same. Explanations should take a deeper look in the processes of the friction layer. This is however not understood until today.

With respect to the investigation of friction and wear in brake systems, totally new aspects of the brake pad interface's dynamics came to the fore in the past few years. Essentially, the boundary layer processes are characterized by specific hard surface structures [8], with a diameter ranging from 50 microns to some hundred 100 microns. These so-called 'patches' are extremely hard and carry the main part of the friction power. Moreover, the patches vary in size, depending on the external loading of the tribological interface. They are permanently generated in the boundary layer but leave the system after a certain period of time [9]. This life cycle leads to an equilibrium of flow of contact patches in the brake pad interface, with the outcome being a dynamic macroscopic friction coefficient [10], whose 'inertia' can be well described by differential equations in the form of special balance equations. Systematic expansions of these balance equations even allow, for the first time, a simulation of different test cycles of the AK-Master test for friction materials with high accuracy [11].

With the help of the cellular automata method, this equilibrium of flow of growth and destruction of friction intensive patches has been used for a detailed description of surface topography [12] and even wear [13], [14]. Thereby, it turned out that the patches represent a very stable pattern of self-organization on

the mesoscopic scale, which apparently protects the soft polymeric underlayer from wear.

Beyond that, the general surface structure of hard patches on a soft matrix motivates new approaches towards an explanation of the brake pad's lateral dynamics at low sliding velocities. Until today, the brake pad interface's dynamics has only been analyzed with respect to changes in topography and patch size over time. For the first time, this paper deals with an analysis of the patches' lateral dynamics, leading to first explanations for a periodic high-frequency friction force, which can be fundamental for the excitation of squealing.

THE PATCH STRUCTURE OF THE TRIBOLOGICAL INTERFACE ON THE BRAKE PAD

The following figure shows a SEM micrograph of a brake pad surface [9].

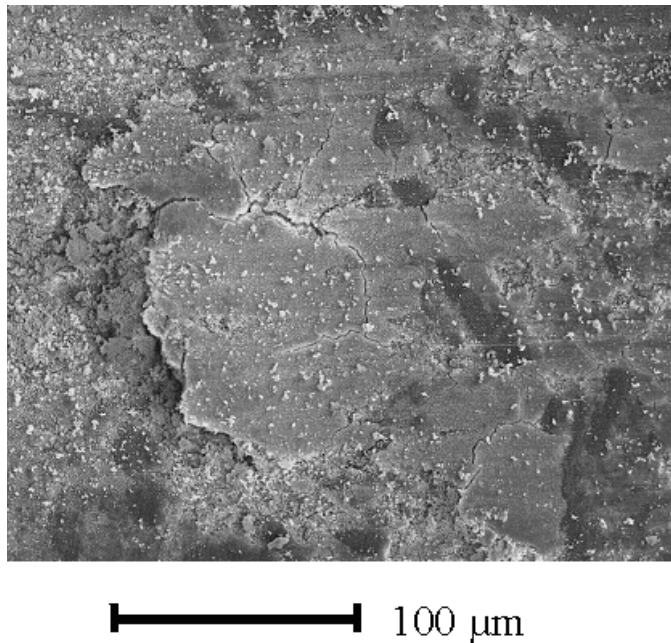


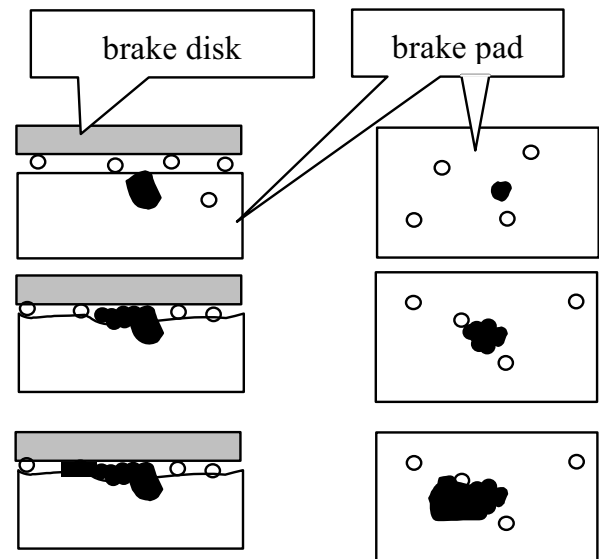
Fig. 1: Patch structures on a brake pad

The observable patches control and determine in a fundamental way the friction and wear properties of the brake system. The basic structure of a brake pad is a comparatively supple matrix with embedded small and hard fibers or particles. An example for an ancient brake material with such properties is wood (e.g. used to slow down windmills at forthcoming storms). Modern brake materials in automotive engineering consist of a soft polymeric matrix with embedded metal fibres, metal swarfs, SiO_2 -particles further hard materials and solid lubricants.

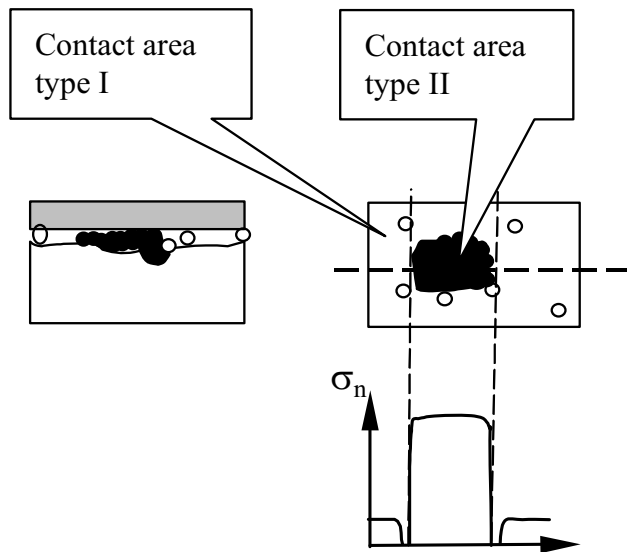
When the brake pad is pressed against the brake disk, wear debris is produced, which at the beginning mainly originates from the polymeric matrix. This debris is similar to the one produced during the process of

rubbing an eraser against a sheet of paper. The wear particles will move through the contact zone and when they reach its rim, a certain fraction will be emitted to the environment, while another adheres to the brake disk. Those particles belonging to the latter fraction will of course move again into the contact zone after a full disk rotation.

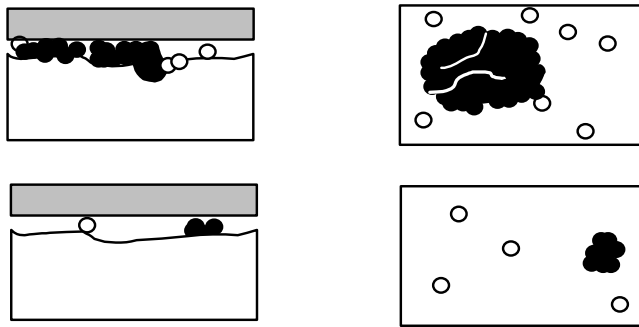
Two important things will happen when, caused by gradual wear of the polymeric matrix, a hard particle reaches the surface of the brake pad. Firstly, due to its high wear resistance, compared with the polymeric matrix, the particle will get pressed down into the matrix. Secondly, the wear particle flow in the boundary layer will be disturbed. As a result of the increasing local normal and tangential stress in the surroundings of the particle, the local temperature will also increase. For technical brake systems, stress and temperature may rise up to a range at which alloying processes between the hard particle and the flowing wear debris occur (some analysis indicates even the possibility of a creation of ceramic structures). This will lead to an accretion of hard and thin contact patches on the friction material, in the opposite direction to the wear particle flow.



(a)



(b)



(c)

Fig. 2: Side view left, top view right: (a) birth of a patch on the brake pad surface. (b) different contact zones and the principle normal load along the dashed line. (c) destruction of a patch

With this generation of contact patches, the brake material surface can be divided into two different contact zones. The contact zone of type I is defined by the contact of the polymeric matrix and the contact zone of type II is defined by the hard patches. The main energetic conversion takes places at the contact zone of type II. Thus, the major part of the braking power is dissipated in this zone. The wear around the contact patches, in conjunction with heat generation and mechanical stress, leads to a growth of cracks on the hard contact patches. Furthermore, the asperity structure of the brake disk enforces local movements/vibrations of the contact patches on the soft polymeric structure and also arouses a crack propagation. These effects result in a destruction of the contact patches after a certain period of time.

The dynamic equilibrium of accretion and destruction of contact patches is a substantial property of the contact areas A_2 (type II) and a fundamental consequence of wear. With the use of a cellular automaton, we reproduced this interaction [12], [13], [14] and as a result, we precisely obtained the well known surface structures of a brake pad.

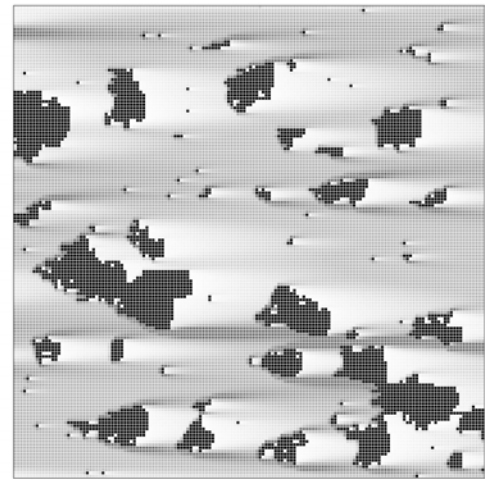


Fig. 3. The brake pad surface with wear debris (gray) and hard patches (black) computed by a Cellular Automaton [12].

Figure 3 shows a section of approximately $1,5 \times 1,5$ mm of the brake pad surface, with the disk moving from left to right.

THE VIBRATION MODEL OF THE BRAKE PAD WITH PATCHES

The real structure of the brake pad interface is quite complex and consists of very different scenarios concerning the contact between pad and disk. Firstly, there are the contacts between the hard patches and the brake disk. These have been described in detail in the previous section and are labeled as type 'II' in Figure 4. Beyond that, a contact between the pad's polymeric matrix and the disk is possible (labeled as type 'I' in Figure 4), as well as a contact between these two that is established via loose wear particles (also labeled as type 'I' in Figure 4).

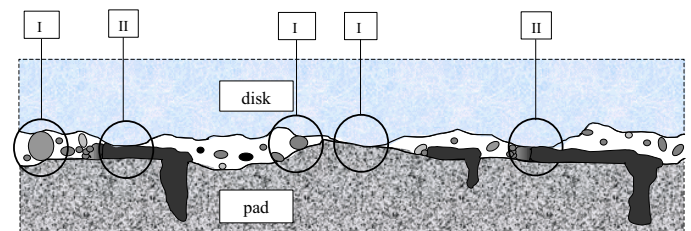


Fig. 4. Contact scenarios between brake pad and disk

Each of these contacts contributes to the tribological behavior of the brake pad on the disk. Beyond that, each of these contacts can be idealized as a friction element with a respective normal force N and friction force R . Each of these elements is elastically coupled to the pad underlayer in normal and tangential direction (via the polymeric matrix), but moreover, all friction elements are elastically coupled with one another (Figure 5). The depicted model is currently being implemented into a cellular automaton. Future work will be devoted to this research topic.