

Investigations on Tribological Memory Effects in Friction Materials

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ABSTRACT

Friction materials for automotive brakes are known to exhibit a time-dependent tribological behavior. When examining these dynamic effects special demands are made on the measurement device: The influences of the brake system should be minimized and parameters like velocity, contact pressure and temperature should be controlled closely and independently. Furthermore, special test procedures need to be designed. This can ideally be achieved using a scaled tribometer like the High-Load-Tribometer at the Institute of Dynamics and Vibrations in Braunschweig.

Former investigations [1] have shown that a kind of memory effect can occur for a low-met brake pad rubbing on a cast iron disk. A variation of the initial disk temperatures has revealed that a temporary increase of the coefficient of friction can occur at slightly elevated temperatures. This effect is memorized by the material as a certain procedure needs to be performed in order to achieve a regeneration. The scope of the current work is to extend this examination with respect to different materials and also include different load cases. It will be studied if effects, like the formerly described, are limited to certain materials and what conditions enable their occurrence.

CITATION: Wilkening, L., Paul, H., and Ostermeyer, G., "Investigations on Tribological Memory Effects in Friction Materials," *SAE Int. J. Passeng. Cars - Mech. Syst.* 7(4):2014, doi:10.4271/2014-01-2481.

INTRODUCTION

The development process of friction materials is driven by a variety of constantly increasing requirements. Besides the tribological behavior also the physical and chemical properties as well as comfort issues have to be considered. In order to master these challenges, very complex material formulations are necessary. In many cases a brake pad consists of more than 20 different ingredients, each fulfilling a different function. Despite some progress in the last years, the prediction of tribological properties using simulations is still quite demanding and therefore testing is the key for the evaluation of friction materials.

In this paper, the main focus lies on experimentally characterizing the tribological performance of the friction material itself. Generally, the goal is to perform a detailed and precise examination of the material's tribological performance at various input parameters. Additionally, possible variations in the behavior of the coefficient of friction are to be identified. These effects are sometimes also referred to as "frictional discontinuities" although the term is mathematically differently

defined [1]. In order to attain this goal the influencing parameters should be kept constant wherever possible. Besides the main parameters contact pressure, relative speed and temperature also the load history and environmental influences like humidity should be regarded. This places special demands on the measurement device, which can best be achieved by using a down-scaled tribometer. Thus, the influence of the brake system (e.g. caliper deflection or effectiveness of piston) can be avoided. Additionally, a direct measurement of the normal and frictional force can be applied due to the absence of the hydraulic system and the better availability of space. Keeping in mind that the goal is to characterize the friction material itself and not the overall performance of the brake system, the reduction of the test specimen's size offers some advantages: When keeping the contact pressure identical as in the full scale test, the total friction power is reduced. Therefore, the required driving torque of the motor is greatly reduced and the need for additional flywheel masses is eliminated. This allows for tests with constant or even increasing speed during the brake application over a wide range of normal loads. Additionally, the decreased

friction power leads to a reduced heat flow into the disk and the test specimen. Thus, the temperature increase during each brake application is greatly reduced. This is very useful when investigations should be performed in a narrow temperature range or when the influence of the temperature itself is to be investigated. Furthermore, the duration for cooling down of the disk is greatly reduced what allows for a higher number of applications to be performed in the same time.

In order to realize the advantages of the down-scaled tribometer, a customized test procedure has to be applied. When investigating the influence of one parameter it is useful to keep all other parameters constant. Therefore, the relative speed and the contact pressure are chosen to be constant during each brake application. The temperature increase during the brake application is minimized by a decrease of the test specimen's size and possible environmental influences are minimized by conducting the tests in an air-conditioned environment. Furthermore, a large number of brake applications with identical input parameters have to be conducted when determining the stationary coefficient of friction and possible variations from it ("frictional discontinuities"). Additionally, a stepwise change of one input parameter can be applied to study adaption processes in the friction process and to determine time constants which describe this adaption.

The friction process in the boundary layer between the brake pad and the disk is mainly governed by the generation and destruction of hard contact areas (patches) [2, 3, 4]. Therefore, examinations of the boundary layer should be included in friction studies as they can contribute valuable information for the interpretation of the test results. The observation of the boundary layer can be done in situ by using a diaphanous disk [e.g. 5]. This approach has the disadvantage of changing the material of one friction partner (disk). Another approach is to apply a sequential combination of friction test, wear measurement and observation of the test specimen's surface [e.g. 6]. This approach does not allow for studying the processes during the brake application but it allows for attaining a snapshot of the test specimen's surface at the end of the brake application while keeping the original friction partners unchanged. This concept was applied to examine the influence of relative speed [7] and initial disk temperature [1] on the friction process. In [1] it is shown that slightly elevating the initial disk temperature can cause a temporary increase of the coefficient of friction. In order to regenerate the friction material, a relatively large number of brake applications at lower temperatures have to be performed. Therefore, this effect can be regarded as a memory effect. The investigations in [1] are limited to one low-met friction material at one relative speed. Therefore, the goal of this paper is to perform similar examinations with an extended scope by including investigations at lower relative speeds and by adding additional friction materials.

EXPERIMENTAL SETUP

Test Equipment

The friction tests are performed on the High-Load-Tribometer at the Institute of Dynamics and Vibration (IDS) in Braunschweig, Germany. The tribometer is based on a conventional lathe and uses the pin on disk test configuration. It can be operated at rotational speeds up to 2080 rpm and normal forces up to 1000 N. The temperature can be measured both in the pin and the disk. For the study of the temperature's influence, the disk can be heated using two hot air guns and a heating chamber. Detailed information on the High-Load-Tribometer can be found in [6,8].

Investigations of the test specimen's surface are performed with a light optical stereomicroscope. The illumination can either be done from the top by a coaxial ring light or by a side light. The coaxial ring light assures a homogeneous illumination of the test specimen and allows for the identification of different materials and structures. The side light also enables the identification of specific structures, especially contact patches and accumulated wear debris. Additionally, it gives a good impression of the surface topography by casting of shadows. The microscope is equipped with a digital CCD camera for taking images of the test specimen's surface. In the following examinations only images using side light are discussed as they include all necessary information.

Friction Materials

Investigations are conducted for two different commercially available friction materials. One material is chosen to be a low-met friction material (same material as used in [1,7]) and the other one is a NAO friction material. Before cutting out the test specimen, the upper layer of the brake pad, which might be affected by the scorching process, is removed by grinding (3 mm). The size of the test specimens is 10 × 20 mm. A thermocouple is glued into the test specimen from the back side. The position of the measuring tip is 2 mm below the surface. The test specimens are implemented in the tribometer in such a way that the longer side is aligned with the relative motion.

The applied cast iron disks are internally ventilated and have an outer diameter of 312 mm and a thickness of 25 mm. The friction radius is 128 mm for the tests with the low-met friction material and 145 mm for the NAO friction material. Thermocouples are glued into the disk from the back side in the middle of each rubbing path. The measuring tips are positioned 1 mm below the surface.

Test Procedure

The design of the test procedure reflects the considerations made earlier. The purpose is to study the influence of the temperature on the friction process. It consists of four sections with varying initial disk temperatures, see [Table 1](#) and [Table 2](#). The initial disk temperature is changed in between the sections what ensures an almost stepwise change. In each section, 32 brake applications are performed at identical input parameters. In all tests the duration of one brake application is 5 s and the

contact pressure is remained constant at 1.34 N/mm² (equates to a brake line pressure of approx. 30 bar). The two presented test procedures differ only in the applied relative speeds. In the first test procedure the relative speed is 9.7 m/s (equates to a vehicle speed of approx. 80 km/h) and 3.6 m/s in the second test procedure (equates to a vehicle speed of approx. 30 km/h). In all cases the relative speed is kept constant during the brake application. At the end of each section, images of the test specimen's surface are taken with the microscope. Both test procedures are carried out subsequently with the same test specimens. The friction couple is subjected to a bedding process before and in between the actual test procedures.

Table 1. Test Procedure 1: High relative speed

Section	Number of applications	Relative speed in m/s	Contact pressure in N/mm ²	Initial disk temperature in °C
1	32	9.7	1.34	40
2	32	9.7	1.34	100
3	32	9.7	1.34	200
4	32	9.7	1.34	40

Table 2. Test Procedure 2: Low relative speed

Section	Number of applications	Relative speed in m/s	Contact pressure in N/mm ²	Initial disk temperature in °C
1	32	3.6	1.34	40
2	32	3.6	1.34	100
3	32	3.6	1.34	200
4	32	3.6	1.34	40

RESULTS

Instead of plotting the measured coefficient of friction as a function of time, a special way to represent the results is used in the following figures. In order to condense the contained information five characteristic values are extracted, see [Figure 1](#). This way, a large number of brake applications can be included in one plot while keeping the key information. A similar approach is applied for the temperature of the test specimen. In this case only the average (circle) and the beginning and end temperature (lower and upper end of vertical line) are displayed. The change in the disk temperature within one brake application is usually less than 5 °C and therefore only the average values are presented.

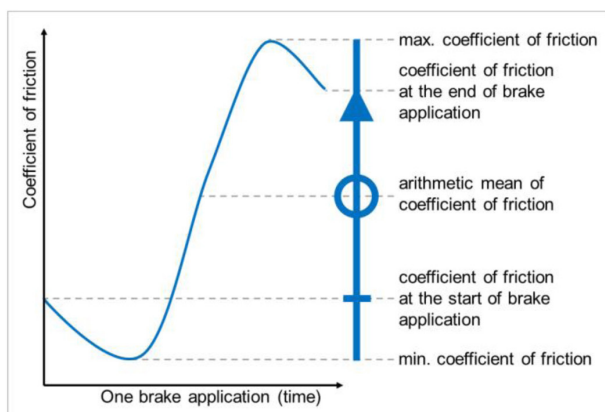


Figure 1. IDS representation of the coefficient of friction during one brake application, based on [7]

Low-Met Friction Material

Results at High Relative Speed

The friction coefficients measured at high relative speed using the first test procedure are presented in [Figure 2](#). In the first section (initial disk temperature: 40 °C) the coefficient of friction exhibits a very stable behavior. This indicates that the bedding process is completed and a stationary friction level is reached. When the initial disk temperature is increased to 100 °C the coefficient of friction is first increasing and afterwards decreasing again. This effect has already been observed and identified as a tribological memory effect in [1]. However, in the present results the increase is beginning directly after the temperature increase and its duration is longer. The reason for this is that in the present examinations the friction measurements are conducted directly after each other without interruptions for taking microscope images. When the temperature is increased to 200 °C in the third section the decrease is still not fully completed. Therefore, the decrease at the beginning of this section is not a result of the increased temperature but rather a continuation of the preceding effect. Afterwards the coefficient of friction reaches a stable level which is slightly higher than at 40 °C initial disk temperature. The variation of the test specimen's temperature in this section is caused by short interruptions that are needed to adapt the disk temperature to the desired level. In this time the test specimen is cooling down. These short interruptions have no major influence on the resulting coefficient of friction and are therefore not discussed in detail. When the disk is cooled down to 40 °C in the last section, the coefficient of friction does not exhibit major changes as it quickly returns to a comparable level as in the first section.

Looking at the behavior of the coefficient of friction during the brake application it can be stated that generally a rising characteristic is observed (indicated by upwards pointing arrow). At low temperatures (40 °C) this characteristic is more distinct than at elevated temperatures (200 °C). The short-term behavior of the coefficient of friction during the brake application is also affected by long-term effects that are lasting for more than one brake application. Therefore, the general increase during the brake application (short-term effect) is superimposed by the temporary increase of the coefficient of friction in the second and third section (long-term effect). Added up, this causes a higher increase at the beginning of the long-term effect while towards the end also a declining behavior during the brake application can be found.

The microscope images taken at the end of each section show that the initial disk temperature does not cause considerable changes of the surface of the test specimen see [Figure 3](#). In all cases some contact patches (darker areas) and almost no loose wear debris (red looking areas) can be found. The interpretation of the images with respect to the influence of the initial disk temperature is further complicated as the image at 100 °C is taken at the end of the second section while the coefficient of friction is still elevated. A more detailed investigation of the surfaces during this tribological effect can