Influence of thermal fatigue on the wear behaviour of brake discs sliding against organic and semi-metallic friction materials

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Abstract:
Investigations carried out in the field of automotive braking systems have proved that brake discs are subjected to severe thermal stresses, in particular during repeated braking at high speeds, which cause loss of braking efficiency and damage to the brake discs. The main purpose of this paper is to analyze the wear behaviour of various brake disc materials such as cast iron, chromium steel, and metal matrix composite under the influence of thermal fatigue. After the brake disc samples have been prepared, they are heated to a predefined temperature and then quickly cooled in a water bath. Then, wear tests are carried out using a pin-on-disc tribometer. Two friction materials, one organic and the other semi-metallic, were used for the wear tests. The test results clearly show the influence of thermal fatigue on the structure and roughness of the contact surfaces of all disc samples. With the exception of the semi-metallic friction material against cast iron, the wear rate of other friction materials has increased. Thermal fatigue does not have a significant influence on the friction coefficient. The worn surface of the metal matrix composite sliding against the semi-metallic friction material is characterized by the abrasive and adhesive wear mechanism.

Keywords: Thermal fatigue, brake disc, brake pad, wear behaviour, hardness, friction coefficient, friction materials.

1. INTRODUCTION

The main function of the braking system is to slow down or stop a vehicle by transforming kinetic energy into heat. In sliding contact zones of tribological systems, take place complex physical and chemical interfacial processes, which are rarely known in detail quantitatively and in practice often not qualitatively. These processes often have a greater influence on wear than on the friction coefficient. It can even remain constant and wear can vary considerably according to load conditions. Increasingly severe loads on the friction components lead to higher operating temperatures, which lead to degradation of the organic composite materials of the brake pads. This will reduce the safety brake performance (falling friction coefficient, increasing stopping distances, and increase brake wear). Many studies have clearly shown the significant influence of braking time, braking speed and number of braking cycles on the increase in disc - pads temperature and thus on the thermal stress [1],[2],[3],[4]. An irregular rise in the temperature of the different parts of the disc, where one part expands faster than another, causes internal stresses. All thermal stresses are referred to as thermal fatigue. Thermal fatigue of brake discs leads to deformation of the discs, which can cause high vibrations and a degradation of braking efficiency. In the case of severe thermal stresses, this even leads to micro cracks in the disc [5], [6]. Investigations on thermal fatigue of brake discs have focused on the real conditions of formation and propagation behaviour of micro-cracks [7], [8].

The purpose of this work consists in experimental analysis of thermal fatigue effect on the wear behaviour of brake disc materials (cast iron, chromium steel, aluminium metal matrix composite (A359 / SiCp)) against pin friction materials and also, in examining the correlation between wear resistance and hardness for the different material pairs tested before and after the thermal fatigue experiments. For the brake pads, two different friction materials were used, one organic and the other semi-metallic. The disc specimens were heated in an electric oven at a defined temperature and right after cooled by immersion in cold water at 25° C. Wear experiments were conducted using the tribometer of the tribology laboratory at the University of Applied Sciences Zwickau Germany

2. MATERIALS AND PROCEDURE

2.1 Materials

In order to achieve good thermal performance and wear resistance, the ideal material for brake discs must be able to store a large amount of heat without deformation or give rise to micro-cracks. During braking, it is desirable to have a high friction coefficient and a low wear rate. The dry sliding contact disc/pads will be assimilated to a couple pin on disc. For tribometer tests, three types of brake disc materials have been selected, the cast iron FG 25 (a conventional material widely used for brake discs of vehicles), the aluminium metal matrix composite (A359 / SiCp) and the chromium steel (only used for comparative purposes). The diameter of the disc is 100 mm, with a thickness of 10 mm, whereas the friction radius is between 20 mm and 30 mm. The friction materials selected for the axles are respectively the organic material commonly used in automotive brake linings and the semi-metallic material used generally in aircraft brake linings. In order to determine the composition of the different constituents of the selected disc and pin materials, samples were observed before and after each test in scanning electron microscopy (SEM), and then analysed by X-ray diffraction (XRD).Table 1 presents the simplified weight elementary composition (in weight percent) of the organic and semi-metallic pin materials obtained by the EDX analysis. The semi-metallic pin material is characterized by a higher content of metallic elements than that of organic matrix composite material.The pins are in cylindrical form with a diameter of 9.5 mm and height of 10 mm. The densities of the organic and semi metallic pins are 0.0025 g/mm3 and 0.006 g/mm3, respectively.

2.2 Thermal fatigue test

Before analysing the effect of thermal fatigue on brake disc wear behaviour, all prepared disc samples (polished disk sample with thermocouple housing hole) were heated in an electric oven to a defined temperature and then cooled by immersion in cold water. This test procedure was chosen because a high temperature tribometer was not available in the laboratory

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	Materials	
Elements	*Organic matrix composite*	Semi metalic matrix composite
Fe	48.77	58.83
Cu	-	15.13
Al	2.98	4.09
Si	2.46	1.57
Mo	-	7.80
Others	45.79	12.58

Table 1: Composition simplified of the organic and semi-metallic pins obtained by the EDX (in weight percent).

The purpose of this test method is to create the phenomenon of thermal fatigue and therefore changes in the structure of the material, especially at its surface. The disc specimens were subjected to a number of heating-cooling cycles to accelerate the thermal fatigue process. The maximum heating temperatures chosen for each brake disc material corresponded approximately to those reached by the brake discs during the braking phase [9]. To reach these heating temperatures, a time of 4:30 min is required for cast iron and chromium steel discs and 2:30 min for composite discs. The initial sample temperature is 25°C. The cast iron and chromium steel disc samples are heated up to 630°C and the metal matrix composite samples are heated up to 330°C and cooled down to initial temperature . This heating temperature was measured continuously by a thermocouple Type K, housed in a hole drilled in each disc specimen. Further, 60 heating/cooling cycles representing laboratory test conditions were performed to experimentally simulate the thermal fatigue test corresponding to the number of repeated braking [9]. After each thermal fatigue test, the analysis of the layer formed on the disc specimens was performed successively with XRD and SEM.

2.3 Wear test

The wear test of pin-on-disc is away the tribological performance of dry sliding contacts to be evaluated. Gravimetric measurements were performed for each sample using an electronic balance before and after each test. The wear rate (Ws) for the distance travelled (L) by the disc during sliding and mass loss (Δm) of density (ρ) was calculated using the following formula:

$$Ws = \Delta m / \rho L \quad (1)$$

The experimental tests on the tribometer for the evaluation of the tribological characteristics of each pair of pin-disk were carried out under the following operating conditions: the velocity Ω= 1200 RPM, normal load Fn= 200 N, friction radius R=30 mm and initial temperature of 25°C. At the beginning of each test, the test chamber is at a temperature of 25°C and a relative humidity of 25%. The time of each wear test is 120 seconds. Each test will be repeated at least 8 times and the average of the recorded measurement data will be calculated [10].

3. RESULTS AND DISCUSSION

3.1 Analysis of the disc contact surfaces after the thermal fatigue process

Fig. 1, 2 and 3 present the XRD spectrum of the layer formed on the contact surface of all disc specimens subjected to the thermal fatigue test and SEM Observations. This analysis shows the presence of iron, iron oxide (FeO) and magnetic oxide or magnetite (Fe_3O_4) as the majority elements of the layer formed on the specimens of chromium steel and cast iron, Fig. 1(a) and 2(a). In the case of the metal matrix composite, the layer formed on the surface was negligible compared to those of the other materials. This layer shows only the composite components, such as aluminium (A1), silicon carbide, silicon and zeolite (SiO_2), Fig.3 (a). The latter component results from the absorption of water during the cooling phase. On the other hand, after a determined number of thermal fatigue cycles, micro cracks appear on the contact surfaces of the disc specimens and are observed on the micrographs, Fig. 1 (b), 2(b) and 3(b).

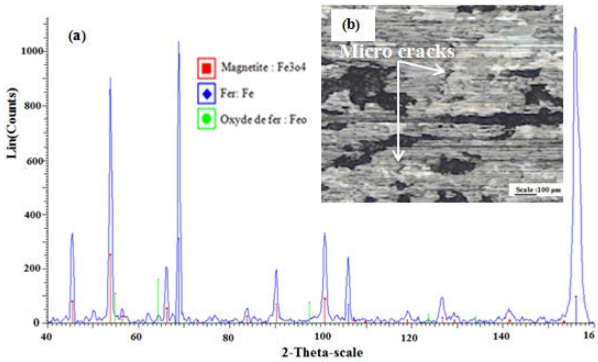


Fig. 1 Results after the thermal fatigue test of cast iron
(a): XRD spectrum, (b): SEM Observation of the contact surface.

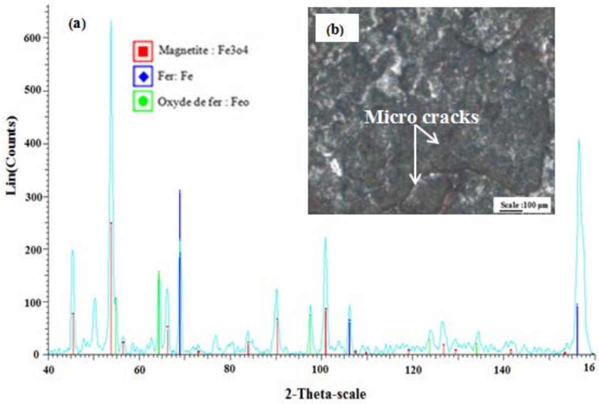


Fig. 2 Results after thermal fatigue test of chromium steel
(a): XRD spectrum, (b): SEM Observation of the contact surface.

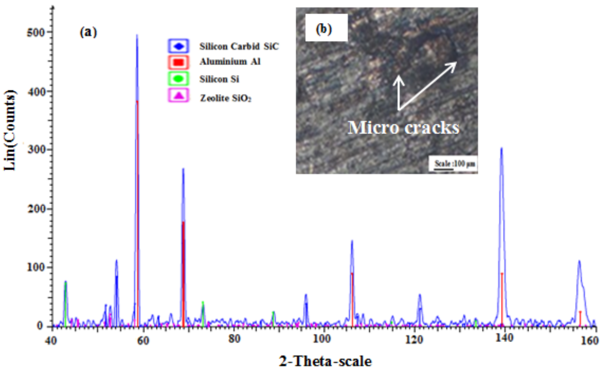
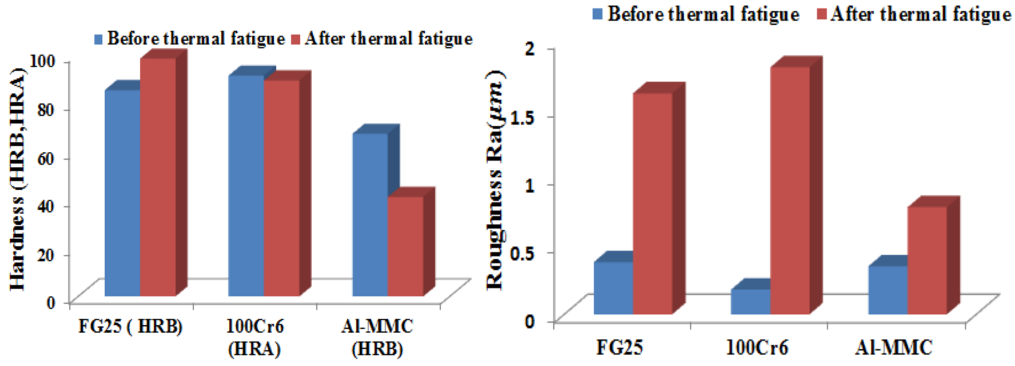


Fig. 3 Results after the thermal fatigue test of the metal matrix composite
(a): XRD spectrum, (b): SEM Observation of the contact surface

Hardness measurements of the three brake disc materials before and after the thermal fatigue test were performed according to the international standard ISO 6508-1 [11]. However, this measurement showed the existence of surface hardening of the cast iron material (FG25). According to Fig. 4(a), the hardness of the cast iron increases after the thermal fatigue test and that of the chromium steel remains almost constant, while that of the metal matrix composite decreases. These results show that despite a much lower heating temperature of the metal matrix composite, it was more affected by thermal fatigue than the other materials tested. Fig. 4(b) shows the surface roughness of all disc materials examined before and after the thermal fatigue tests. The surface roughness of chromium steel 100Cr6 and FG 25 are the most affected. The thermal fatigue test can be compared to a hardening process.



(a) (b)

Fig. 4 Hardness (a) and Roughness (b) of the brake disc materials before and after the thermal fatigue test.

3.2 Evolution of the wear rate

Since brake pads are subjected to much more wear than the brake disc, this study is focused on wear tests of organic and semi-metallic friction materials. Fig. 5 (a) and 5 (b) present the variation of the wear rate for both organic and semi metallic friction materials sliding against brake disc material before and after thermal fatigue tests. An increasing wear rate for all of the materials that underwent the thermal fatigue process is observed. This increase varies between 25% and 55%, except the semi-metallic pin sliding against the cast iron disc with a wear rate diminution of 34%.

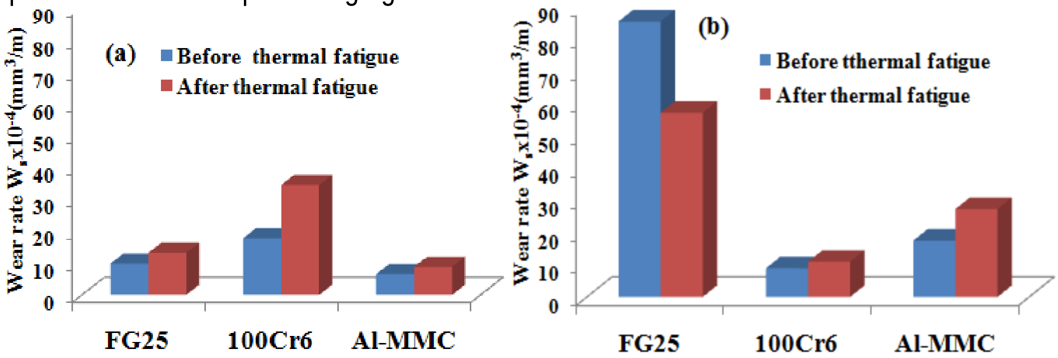


Fig. 5 Effect of thermal fatigue on the wear rate pin material:
Organic friction material and (b) Semi-metallic friction material.

4. CONCLUSION

The first objective of this work was the approximatively reproduction of the high stresses encountered in service on an experimental laboratory device. The pin and disc materials selected to carry out the tests are those generally used in automotive and aeronautical braking systems. Disc sample materials are cast iron, silicon particle reinforced composite aluminium and chromium steel; pin materials are organic and semi-metallic. The wear behaviour of different combinations of disc and pin materials was evaluated using the gravimetric method.

Based on the tests carried out, apart from the cast-iron sliding against the semi-metallic material, there was an increase in the wear rate of friction materials because of structural changes in the roughness of the contact surface due to the thermal fatigue process. Thermal fatigue weakened the surface layer of the materials and consequently reduced their hardness, which was verified by the results of roughness and hardness measurements before and after the fatigue test. Concerning the evolution of wear of composite discs is concerned, their wear mechanism is characterized by abrasive and adhesive wear, whereas that of other materials tested solely by abrasive wear; It should be noted that after thermal fatigue testing, the best wear behaviour is observed with cast iron sliding against organic friction material and chromium steel sliding against semi-metallic friction material.

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