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A preliminary investigation on the use of the pin-on-disc test to simulate off-brake friction and wear characteristics of friction materials

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ABSTRACT

During off-brake driving, some unwanted contact between the brake pads and the rotating discs may occur, thus inducing inefficient fuel usage and additional environmental pollution. This paper addresses the frictional behavior of 5 commercial low-met and NAO friction materials dry sliding against a cast iron counterface disc, under low contact pressures, typical of off-brake driving. In the investigated conditions, kinetic and static coefficient of frictions (COFs) were found to be independent from the contact pressure. The static COFs were all found to be around 0.2, whereas the kinetic COFs were found to be higher in the low-met materials with respect to the NAO materials and they were found to be roughly independent from the contact pressure. The results were explained with reference to the adhesive theory of friction, highlighting the paramount role of the Fe-oxides embedded in the friction layer.

1. Introduction

In automotive braking systems, the friction forces between stationary pads and a rotating disc allows the vehicle to stop. Friction also induces an energy dissipation, associated with a material wearing out, that results in a thermal load on the brake parts and emission of wear particles in the environment [1,2]. Even during off-brake conditions some unwanted contact between the pads and the disc may occur, because of the imperfect alignment between the disc and the pad, disc distortions, or an imperfect caliper operation. Therefore, frictional energy may be also dissipated in off-brake conditions, and this contributes further not only to the emission of wear particles but also to a less efficient engine combustion, with increased CO_2 emissions. It is reported that 1 Nm drag torque at each wheel may induce an emission of 2 g CO_2 per km [3]. It would be clearly preferable to have friction couplings capable to guarantee a relatively high Coefficient of Friction (COF) during normal braking conditions, i.e., a COF in the range 0.3–0.6, and a lower COF in off-brake conditions, when the contact pressure is low, below 50 kPa [3], to be compared with pressures in the 1–3 MPa range for conventional braking.

Nowadays, rotor discs for vehicular brakes are typically made of pearlitic cast iron and pad materials are composites, containing even more than 30 ingredients, and often classified as low-metallic (low-met) and Non Asbestos Organic (NAO) materials [4,5]. Several investigations have demonstrated that the COF and system wear depend on the characteristics of the friction layer that forms at the pad-disc contact region, which in turn depends on the composition and characteristics of the mating materials. The friction layer is made of primary and secondary plateaus (called also ‘patches’) [6–9]. Primary plateaus consist of hard particles and fibers, even metallic, protruding from the pad surface. Secondary plateaus are made of wear debris that pile up and are compacted against the primary plateaus. The specific features of the friction layer determine the frictional and the wear behavior of the sliding system, since such plateaus are responsible for the transmission of the friction force from the pad to the disc [6,10]. In general, at the beginning of sliding, a run-in stage is required to form an effective friction layer [11]. During this stage, wear debris result from the wear of the pad and the possible fragmentation of the friction layer, together with the abrasive and tribo-oxidative wearing out of the cast iron disc. This latter mechanism results in the formation of small iron oxides, typically magnetite and hematite [12], particles. Such smaller debris are able to pile-up and form the main components of well compacted secondary plateaus, a prerequisite for a smooth and stable COF. On the other hand, less compacted secondary plateaus generally determine an evolution of the coefficient of friction characterized by a larger scatter, because of the dynamic fragmentation and reformation of the contacting plateaus [9]. The presence in the friction material of such elements as copper, graphite, and other soft components, like metal

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sulfides, promote the formation of well compacted secondary plateaus [12]. A recent investigation by Lee and Filip [13], has confirmed further these observations with reference to the friction and wear behavior of different NAO materials. In the case of the friction materials containing Cu, barite and other ingredients, particularly prone to adhere with each other, a stable friction layer was obtained during sliding and a lower level of friction and wear was detected. In different investigations [12,14,15], Österle et al. also showed the paramount role played of solid lubricants, such as graphite, in the compaction of iron oxide, namely magnetite (Fe_3O_4), particles to form dense secondary plateaus. Of course, because of the presence of different ingredients in the secondary plateaus, the values of the friction coefficient were found to be lower than 0.8, a typical reference value exhibited by the steel-steel contact under tribo-oxidative conditions [12,16].

In the present work, we investigated the friction behavior of five commercial friction materials, sliding against a pearlitic cast iron. The kinetic COF was measured using a Pin-on-Disc (PoD) test rig, operating in drag conditions and at nominal contact pressures between 15 and 50 kPa. Although PoD is not reproducing real braking conditions, it is an excellent tool for verifying preliminarily materials properties and understand the role of the main wear mechanisms, as demonstrated by several investigations [9,10,14,17,18]. To help explaining the obtained results, specific wear tests were also conducted for evaluating the static friction coefficient in the same contact conditions [19]. The aim of the investigation was to determine the friction behavior of typical low-met and NAO brake materials at low contact pressures and to relate the results to the characterization of the friction layer, in particular the secondary plateaus in order to explore the possibility to obtain low values of the COF at low contact pressures.

2. Materials and experimental procedures

2.1. Friction materials

Five different commercial friction materials were investigated. Their elemental composition, as measured by energy dispersive X-ray spectroscopy (EDXS), is reported in Table 1. As a rule of thumb, low-met materials usually contain a total amount of metallic Fe and Cu in the range 10–50 wt%; NAO materials contain a lower amount of metallic ingredients, typically below 10 wt%. The classification is also based on the average values of the COF, since low-met materials would generally feature comparatively high COF, usually in between 0.4 and 0.6, when sliding against pearlitic cast iron discs. NAO materials exhibit lower COFs, usually not exceeding 0.4 [5]. The comparative indications provided by the EDXS results in Table 1 show that the friction materials 1 and 2 can be classified as low-met, whereas material 5 is a NAO. Material 3 and 4 are in between. Considering that in general NAO materials display a lower friction coefficient with respect to low-met materials and on the basis of the results reported later on this work, we can consider material 3 and 4 as NAO.

Table 1
Elemental composition of the friction materials investigated in the present study (the concentrations of C and O are not included in the table).

Element	Friction material 1 [wt%]	Friction material 2 [wt%]	Friction material 3 [wt%]	Friction material 4 [wt%]	Friction material 5 [wt%]
Fe	15.8	26.6	21.2	12.4	0.7
Al	10.3	17.8	13.8	5.6	1.3
Mg	11.5	12.2	13.6	1.0	7.4
Cu	13.7	11.3	–	11.0	–
Sn	9.4	8.0	7.2	4.0	3.0
Zn	15.8	6.8	14.9	3.5	–
Ca	7.6	5.9	5.7	2.5	5.0
S	4.9	4.7	9.3	3.3	4.2
Cr	3.1	3.1	4.0	–	–
Si	6.8	3.1	7.4	3.1	4.2
K	–	0.5	–	3.3	6.1
Na	1.1	–	2.9	5.6	1.3
Zr	–	–	–	27.3	30.6
Ti	–	–	–	14.0	27.6
Ba	–	–	–	3.4	6.8
F	–	–	–	–	1.8

Fig. 1 shows the SEM micrographs of the five friction materials. From the EDXS maps, not included in the present report, the main ingredients have been identified, as indicated in the relevant SEM micrographs. Material 5 is characterized by a fine homogeneous distribution of the constituent phases. All other materials feature a rather inhomogeneous microstructure, containing comparatively coarser ingredients, including metallic fibers or powders, coke particles and abrasives, such as MgO (in friction materials 1, 2 and 3), alumina (materials 1, 3 and 4) and zirconia (material 4).

2.2. Experimental procedure

The sliding tests, aimed at obtaining the evolution of the kinetic COF, were performed in dry sliding conditions by means of an Eyre/Biceri PoD test rig, schematized in Fig. 2(a). The pins had cylindrical shapes and they were machined from commercial brake pads. The diameter of the pins was of 30 mm and the height of 15 mm. The discs are made of a pearlitic grey cast iron with a hardness of 209 ± 3 HV30. The discs were 140 mm in diameter and 15 mm in height. The average surface roughness of the discs (R_a) was equal to 2.2 ± 0.2 µm, for both the PoD and the static friction (*see infra*) apparatuses.

The materials were tested at room temperature and at a nominal contact pressure of 15, 30 and 50 kPa (the load was applied using a dead weight). The sliding velocity was 2.88 m/s in all cases, and the test duration was 1 h. Before each test, a preliminary running-in stage was performed at 200 kPa in order to establish a proper friction layer on the pin surface in a relatively short time (1.5 h). In any case, the parallelism between the PoD arm and the rotating disc was checked before and after each test. During the entire test the COF was continuously recorded. The results presented are the average of at least three different repetitions. Pin wear was also measured by checking its weight before and after each test using an analytical balance with a precision of 10^{-4} g. Data were then converted into wear volumes and the specific wear coefficients, Ka, were calculated by dividing the volume loss for the applied load and sliding distance:

$$K_a = V/(sF_N) \tag{1}$$

being V the wear volume, s the sliding distance and F_N the nominal contact force in N. The worn surfaces of pins were analyzed by means of JEOL IT300 scanning electron microscope (SEM) equipped with an EDXS system. The worn out surfaces of the discs were observed by means of an optical microscope (OM).

The static COF, using both run-in tested and pins and discs in their pristine conditions, was measured by means of the experimental apparatus schematized in Fig. 2(b). In the case of preliminarily PoD tested pins, the same couple used during the wear tests was used. To avoid any possible indeterminations in the actual pressure, due to different contact times between pins and discs, all the tests were performed after 10 s of pin-disc contact [19]. The velocity of the dynamometer was set equal to 0.1 cm/s. The results of these tests are the average of five different measurements for each material.

3. Results

As an example, the top view of the worn out surfaces of the pins of the materials 1 and 4 after the running-in stage PoD tests, conducted at 200 kPa are shown in Fig. 3: well compacted and widely distributed plateaus are visible. The same was observed in the other materials tested at 200 kPa.

The evolution of the COFs is shown in Fig. 4 for the friction