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Effects of humidity and corrosion on the tribological behaviour of the brake disc materials

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ABSTRACT

The aim of the present work was to investigate the influence of humidity and corrosion in a high-salinity environment on the friction and wear behaviour of three brake disc materials. Experiments were conducted using a commercially built disc-on-pin machine (SRV4, Optimal Instruments, Germany). Three different disc brake materials were used: cast iron (type FG25), chromium bearing steel (type 100Cr6) and an aluminium-based composite Al MMC (type A359/SiC_p). The pin in all tests was a commercial automotive brake pad material. The results showed that the friction coefficients and the wear rate for all tested materials were sensitive to increasing normal load and the sliding speed. At increased humidity level, a water film formed and behaved as a lubricant. The corrosion due to salt spray had a larger influence on the tribological behaviour of the cast iron and the chromium steel than it did on the Al MMC. The Al MMC A359/SiC_p exhibited a better tribological behaviour than the other brake disc materials used in this investigation under the given test conditions.

1. Introduction

The friction coefficient of the brake friction material is an important parameter affecting the brake performance and can be used to apprehend various braking phenomena such as stopping distance, fade, nose propensity, pedal feel, and brake-induced vibration [1]. Furthermore, the friction is not an intrinsic property of materials; it depends generally on the tribological system which includes materials, but also the environmental conditions. Numerous experimental studies show that the friction coefficient and the wear rate vary according to interfacial conditions, such as the normal load, the sliding speed, the roughness of rubbing surfaces, the nature of the material, the temperatures and the relative humidity [2–5]. On the other hand, the braking procedure refers to the complex wear mechanisms including abrasion, adhesion, fatigue wear and chemical reactions [6]. Among these experimental results, Liu et al. [7] studied the transfer films of friction material during brake processing. Österle and Urban [8] investigated chemical and microstructural aspects controlling friction and wear of brake materials and they noticed that the main wear mechanism is a delamination of particles from the organic binder, supported by the local degradation of the phenolic resin during asperity heating. Eriksson et al. [9] give a micro- and macroscopic overview of the wear process, where the real contact area is concentrated to small spots confined within the plateaus. The plateaus have a relatively long life while the areas of real contact are constantly shifting due to wear, deformation and surface roughness on the disc surface. Daoud and Abou El-khair [10] showed that the wear rate and the friction coefficient of the friction material sliding against cast iron are slightly lower than the friction material sliding against composite. Hong et al. [11] compared the friction and the wear characteristics of three friction materials with different binder resins, where the wear rate below a critical temperature showed a slow increase, but above, it increased rapidly. However, the investigations concerning the effects of humidity and corrosion on the tribological behaviour of the brake disc materials are very limited. Gao and Kuhlmann-Wilsdorf [12] reported that the humidity could enlarge the contact area of the rough surface during sliding and lead to stick-slip. Eriksson and Lord [13] suggested that addition of the fluid to the contact promoted the formation of larger contact plateaus which play an important role in friction and wear of brake materials. Blau et al. [14] studied the effect of salt spray on the grey cast iron and they noticed that the corrosion acted as an abrasive and reduced the frictional coefficient. Park et al. [15] showed that the corrosion of brake disc significantly induced stick-slip with greater amplitude by transferred oxide product from disc to friction material, and the oxide particles at the sliding interface rendered the

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surfaces of the disc and friction material more hydrophilic. Shin et al. [16] observed that the corrosion of the disc was accelerated because of water condensation. They showed that the friction level, friction oscillation, and wear of the corroded discs were strongly affected by the aggressiveness of the friction material.

The present study is intended to investigate the tribological performance of three different brake disc materials, cast iron (FG25), chromium bearing steel (100Cr6) and an aluminium-based composite Al MMC (A359/SiC_p), sliding against a commercial resin-based brake pad material. The main aim is to analyse the effects of applied normal load, sliding speed, relative humidity, and corrosion due to the salt spray on the frictional behaviour.

2. Experimental procedure

2.1. Materials

The interactions between the material, the mechanical requests and the environment surrounding in a rubbing contact are complex. However, the braking friction materials are intended to maintain a stable friction with considerable friction coefficient. The conducted experiments were carried out with three brake disc materials: the cast iron FG25 as a current commercial material of brake disc which is inexpensive and relatively easy to machine, the silicon carbide reinforced aluminium matrix composite, known as Al MMC A359/SiC_p, supplied by Alcan International (Duralcan designation: F3S.20S) and the chromium steel 100Cr6 which is used for a comparative purpose, knowing that the first disc brakes for automobiles were in chromium steel. All disc specimens are 100 mm in diameter and 10 mm in thickness. Due to the hardness of the Al MMC A359/$SiC_{p,}$ water jet cutting was used to obtain the desired samples. The lining materials of automotive brakes are usually composites and its exact composition is unknown. The pin specimens were manufactured from a commercial resin-based brake pads material used in Fabia Skoda 1.4. Table 1 show their composition realized by means of EDX (Energy Dispersive X-ray spectroscopy). They had 9.5 mm in diameter and 10 mm in thickness and a density of 0.0025 g/mm^3. The micrograph (SEM) of the polished surface of the friction material (pin) is shown in Fig. 1. The dimensions of the pin and the disc are related to the restrictions imposed by the manufacturer of the tribometer.

2.2. Corrosion of test specimen

The corrosion of the test specimens was carried out using salt spray test, according to the standard ASTM B117 [17], it supplies a controlled corrosive environment and gives relative information of corrosion resistance for the tested specimens. The corrosion test consist in pulverizing a salt solution in uniform droplets on suspended specimen. The salt solution contains 5% of NaCl and the salt spray chamber is maintained by an ambient temperature. For each material, it used two specimens, exposed to the salt spray during six days (144 h).

2.3. Test on the tribometer

The essays on the tribometer allow an estimating of the tribological performance of dry sliding contacts on the scale of laboratory. The commercially built disc-on-pin type SRV4 (Optimal Instruments, Germany) [18], as shown in Fig. 2, is composed by an essay chamber with disc-pin, a measurement unit with a display data panel (normal load F_n, rotation speed of the disc Ω, friction radius R, and initial temperature of the disc T_i) and an adjustment unit of test conditions (relative humidity H and ambient temperature T_c) and a display screen. The sliding occurs between a fixed pin, pressed against a rotating disc. The frictional force and the wear depth monitored with an electronic sensors. From the values of the normal load applied on the pin F_n, and the frictional load F_r measured by the tribometer, the friction coefficient μ is calculated as follow:

$$\mu = F_r/F_n \quad (1)$$

To determine the wear rate of the pin, the weight loss was measured by means of an electronic balance with a precision of 1×10^{-4} g before and after each test. The wear rate is calculated according to the following formula:

$$W_s = \Delta m/\rho L \quad (2)$$

W_s is the wear rate [mm^3/m], Δm [g] the mass loss, ρ [g/mm^3] the density and L [m] the sliding distance. Since in this study we used only one friction material under lab-scale conditions, the wear rate expressed by the wear volume divided by the sliding distance Eq. (2) seems most appropriate. To estimate the life of the brake pads using different friction materials, it is preferred to use the specific (or normalized) wear rate equal to the wear volume divided by the sliding distance and the frictional force [19].

The dry sliding tests were carried out by varying the following parameters: the normal load F_n from 10N to 200N, the sliding speed ν from 1.57 m. s^{-1} (Ω=500 rpm) to 5.79 m. s^{-1} (Ω=1800 rpm) and the relative humidity H from 20% to 90%. During all tests, the following parameters were maintained constant: the ambient temperature T_c=25 °C, the initial temperature of the disc T_i=25 °C and the friction radius R=30 mm. Fig. 3 presents the behaviour of the friction coefficient of the composite Al MMC (A359/SiC_p) as a function of the sliding time. During this test, the end surface of the cylindrical pin was pressed against the rotating disc in composite material. A constant normal load of 100N was applied directly on the top of the pin, which yielded a nominal contact pressure. The tests were conducted at constant speed of 1200 rpm (3.76 m.s^{-1}) and constant relative humidity of 25%. The total duration of each test is 140 s, where the first 20 s is intended to reach the fixed rotational speed of the disc. The remaining time is the test duration, where the first 10 s is intended to achieve the defined normal load and to establish the total contact pin disc. After this phase, the effective sliding test begins. Five repeated tests were

Table 1
Composition of the frictional material (pin) realized by means EDX.

Frictional material (pin) (%)												
Mg	Al	Si	S	Cl	K	Ca	Cr	Mn	Fe	Zn	Ba	O
1.03	2.98	2.46	2.61	1.07	0.7	5	0.5	1.26	48.77	0.79	2.83	30

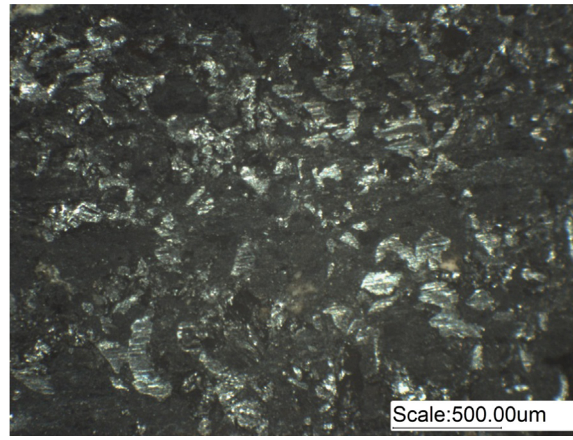

Fig. 1. Micrograph of worn surface of friction material.

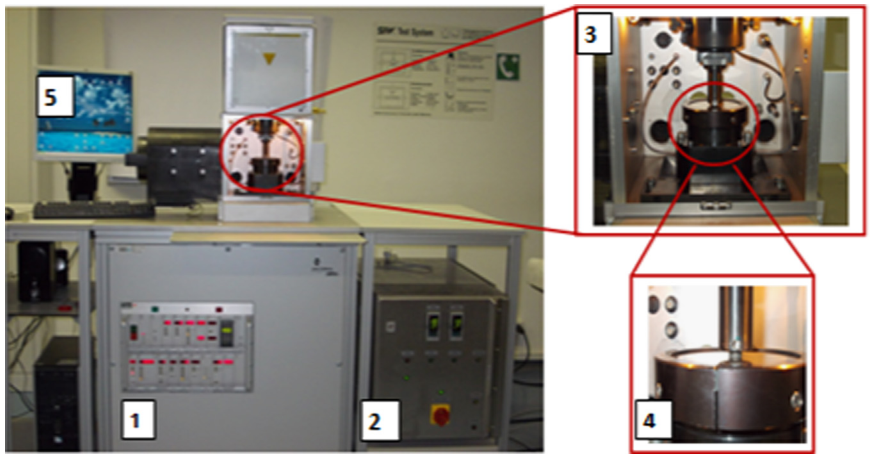

Fig. 2. Disc-pin sliding test on the tribometer SRV 4: (1) measurement unit with a display data panel, (2) adjustment unit of test conditions (humidity and ambient temperature), (3) essay chamber, (4) disc-pin couple, (5) display screen.

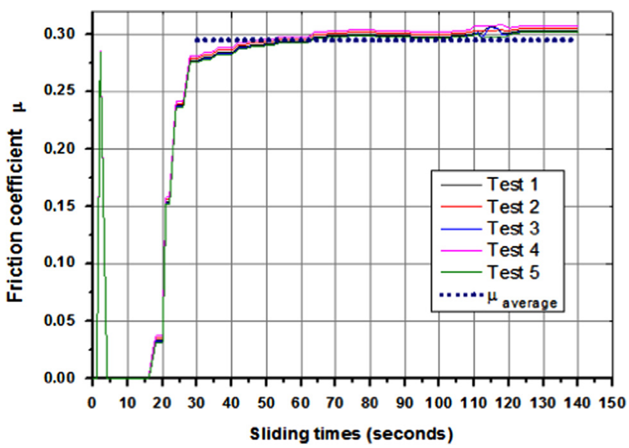

Fig. 3. Friction coefficient of the Al MMC A359/SiC$_p$ versus sliding time.

carried out and the average of the five test results was reported. Before the tests, the pin specimen was rubbed with sandpaper grade 400 to ensure good uniform contact between the two rubbing surfaces, and then the samples (disc-pin) were burnished on the tribometer until they showed a stable friction coefficient.

3. Results and discussion

3.1. *Effects of normal load on the friction coefficient and the wear rate*

The variation of friction coefficient of the tested brake disc materials according to the applied normal load was determined at a constant sliding speed $v=3.76$ m.s^{-1} (1200 rpm) and constant relative humidity $H=25\%$. As can be seen from the Fig. 4(a), the friction coefficient for the cast iron and the chromium steel decreased with increased normal load. Between the normal load and the measured friction coefficient exists an antagonist relationship. This is believed to be caused by an insufficient amount of tribo-layer formation between the sliding interfaces at lower and higher applied normal load [4]. Concerning the Al MMC A359/SiC$_p$, a stable friction coefficient values were observed and the normal load has no effect on the friction coefficient as described in the literature [10]. In Fig. 4(b), the wear rates for all tested materials increased with the normal load and they follow the same behaviour low. This evolution may be due to the quick plastic deformation of material in the contact surface, where the shear forces between asperities increased continuously with normal load. Despite a constant friction coefficient of Al MMC A359/SiC$_p$, the wear rate grows with the normal load. Whereas the trend shows that the friction coefficient and the wear performance do not go together. When the friction behaviour is good, the wear performance is poor and vice versa [20].

3.2. *Effects of the sliding speed on the friction coefficient and the wear rate*

Fig. 5(a) shows the friction coefficients of all brake disc materials tested for different sliding speed at constant normal load $F_n=200$N and constant relative humidity $H=25\%$. Two ranges were observed. In the first zone, where the sliding speed is lower than 3.14 m.s $^{-1}$ ($\Omega=1000$ rpm), the friction coefficient increases rapidly with the sliding speed. In the second zone, it is observed that the friction coefficient for both materials (cast iron and chromium steel) decreases with increased sliding speed, except the friction coefficient of the Al MMC increases. These results are similar to those obtained by [3,19]. By constant test duration, the mass loss Δm of the pin increases with the sliding speed. This trend is valid for the wear rate, because the increase of the mass loss is more significant than the sliding distance (Fig. 5(b)).

3.3. *Effects of the relative Humidity on the friction coefficient and the wear rate*

The effect of the relative humidity on the tribological characteristics of the couple disc-pin was examined by varying the relative humidity in the essay chamber of the tribometer from H $=20\%$ to H$=90\%$ at constant normal load $F_n=200$N and constant sliding speed $v=3.76$ m.s^{-1} ($\Omega=1200$ rpm). The experimental results presented in Fig. 6(a) showed that the friction coefficients of the cast iron increased with humidity from 20% to 40%, and decreased weakly after $H=40\%$. The friction coefficient of chromium steel decreased with increasing humidity. Concerning the Al MMC A359/SiC$_p$, the humidity has a negligible influence on the friction coefficient. In Fig. 6(b), the wear rate follows the same behaviour law for all materials. It decreases as the relative humidity increases despite the application of a high normal load; this is because of the formation of water films on the sliding interface [5]. The aluminium-based composite Al MMC A359/SiC$_p$ is distinguished by a coefficient of friction and a wear rate less important than the chromium steel 100cr6 and the cast iron FG25 (Fig. 6).

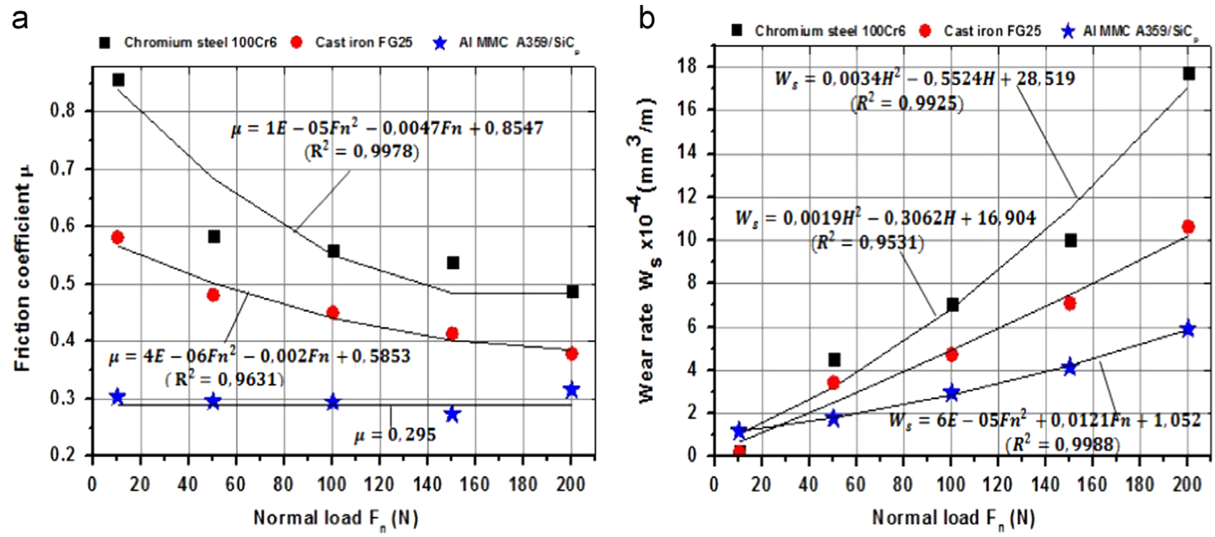

Fig. 4. Influence of normal load on friction coefficient (a) and wear rate (b).

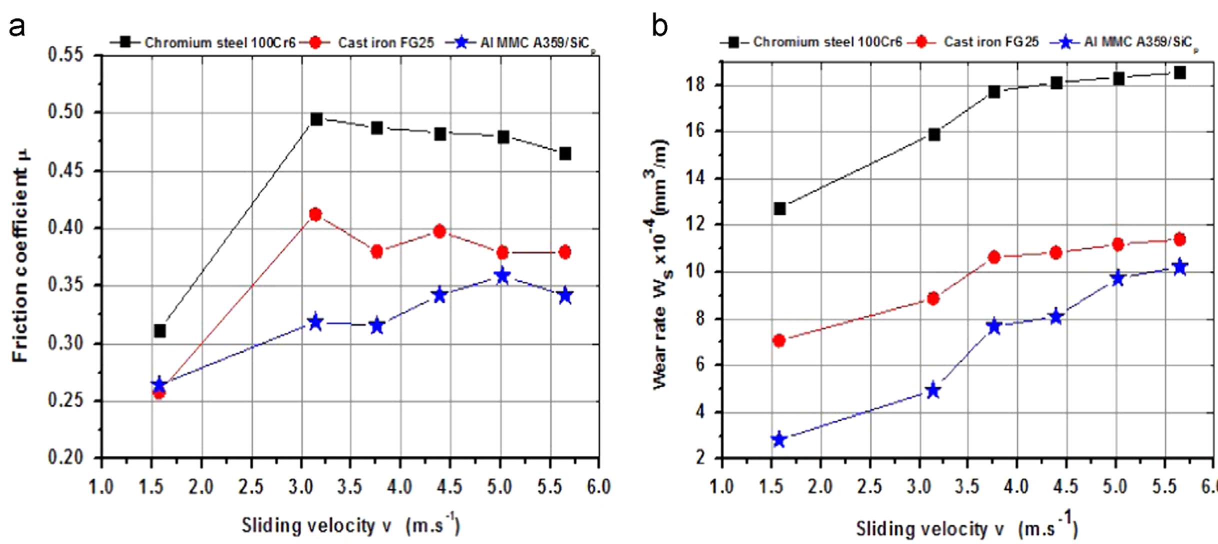

Fig. 5. Influence of sliding speed on friction coefficient (a) and wear rate (b).

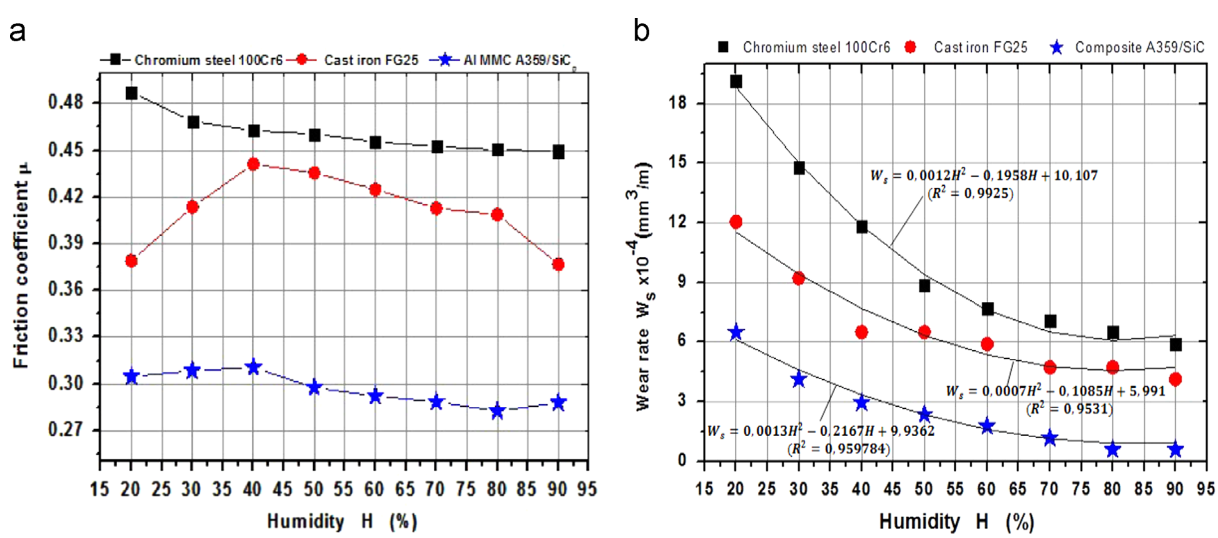

Fig. 6. Influence of relative humidity on friction coefficient (a) and wear rate (b).

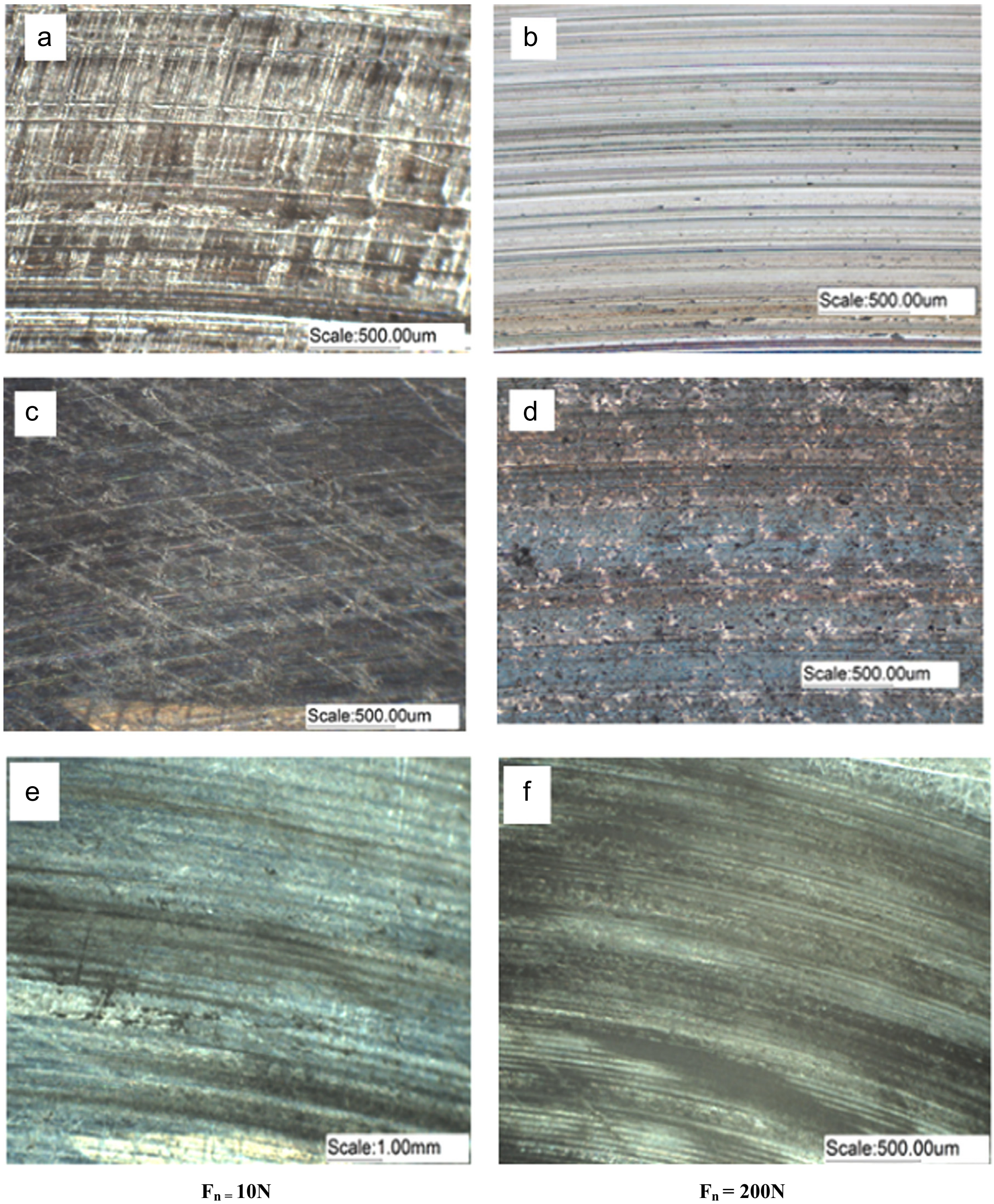

Fig. 7. Micrographs of worn surfaces at normal load $F_n = 10N$ and $F_n = 200N$: (a) and (b) chromium steel (100Cr6); (c) and (d) cast iron (FG25); (e) and (f) Al MMC A359/SiC$_p$.

3.4. Worn surface of the disc

Given that the increasing of the applied normal load has big effects on the wear than the other parameters (the sliding speed and the relative humidity), macroscopic observations of worn tracks were realized after the wear tests on the tribometer at low and high applied normal loads (F_n=10N and F_n=200N). The worn surfaces of all tested brake disc materials are presented in Fig. 7.

There is a significant difference between the state of the worn surfaces at low and high applied normal load. At applied normal load of 10N, the worn surfaces are still rough and exhibit deep sliding marks and only some grooves (Fig. 7(a), (c) and (e)). Numerous grooves resulting from Ploughing of asperities were observed on worn surfaces of all specimens at high applied normal load 200N (Fig. 7(b),(d) and (f)). Furthermore, with increasing applied normal load from 10 N to 200 N, the morphology of worn surfaces changes gradually from fine stripes to distinct grooves, as mentioned by [21]. At high applied normal load, the chromium steel disc has non-uniform worn surface with little deformation and presents parallel grooves due to the abrasion (Fig. 7(b)). The wear grooves show the evidence of severely plastic flow in the form of grooves parallel to the sliding direction. Some pulverulent fragments were observed at the edges of the track of the specimen. The worn surface of the cast iron has parallel grooves in the sliding direction caused by abrasion mechanism, as well as many pulverulent fragments collected on the friction track of the specimen (Fig. 7(d)). At low applied normal load (10N), the worn surface of the Al MMC A359/SiC_p shows dark areas representing the real contact surfaces between pin and disc, and also parallel grooves. The distance between these grooves is longer compared to the others materials, (Fig. 7(e)). With increasing applied normal load up to 200 N, the contact area is increased and it became darker (Fig. 7(f)).

Fig. 8 shows the profile of the worn surface for materials tested, measured by the rugosimeter, Mitutoyo SJ210. For chromium steel, the distance between the asperities is smaller and the depth is higher compared to the other materials. At low contact pressure, the contact surface between the pin and the disc in composite material is smaller than the other materials. The frictional force shows a clear correlation with the groove density. It increases with the number of asperities in the contact area [22]. According to [23,24], with increasing the applied normal load, the total area of micro-contacts increases and the transfer layer is highly compacted. From the experimental results, it is noted that increasing of applied normal load leads to a deformation of the asperities of the contact area and consequently increase the real contact [25].

3.5. Corrosion effect on the tribological behaviour

After an exposure time of six days (144 h) to the salt spray of the specimens in cast iron and chromium steel, the colour of the surface becomes slightly blackish. Also, it observed a multicoloured assembly of minerals oxide iron (black, brown, yellow, orange and red) and a residual crystal of salt transparent clear or yellowish formed during the drying process (Fig. 9(a) and (b)). The colour of the specimens in Al MMC A359/SiC_p exposed to the salt spray became grey mat (Fig. 9(c)). The analysis with the XRD of the corroded

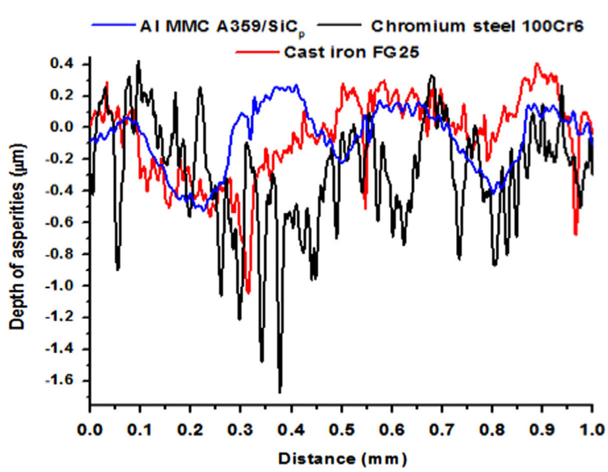

Fig. 8. Profile of the worn surface for materials tested.

surface of cast iron and chromium steel showed the presence of the iron, the iron oxide (FeO) and the magnetic oxide (Fe_3O_4), the content of the latter is dominant. For the composite A359/SiC_p, the XRD provides no information on the composition of the corroded layer. This is due apparently to the low thickness of this layer.

3.5.1. Influence of the corrosion on the friction coefficient and the wear rate

Fig. 10(a) shows the values of the friction coefficient for all tested materials before and after corrosion. The friction coefficient depended on the type of materials and on the exposure time to the corrosion. The exposure to the corrosion of the materials during six days (144 h) produced a decrease in the friction coefficient of 40% for FG25, 25% for chromium steel and 5% for the composite. The Al MMC A359/SiC_p is better resistant to the corrosion caused by salt spray.

Fig. 10(b) showed the evolution of the wear rate of the pin in contact with the non-corroded and corroded disc for the three tested materials. The wear rate of the pin sliding against the disc in Al MMC A359/SiC_p is less affected by the corrosion than with the other materials. According to the previous figure (Fig. 10), the influence of corrosion on the tribological behaviour of the tested brake disc materials is visible. The decrease in friction coefficient and wear rate is due to the fragility of the corroded contact surfaces (decrease of the shear strength of asperities).

3.5.2. Micrographs of worn surfaces

The worn surfaces of the contact area of the two corroded specimens in cast iron and chromium steel show the presence of the magnetite (Fe_3O_4), which plays a role of abrasive in the degradation of surfaces (Fig. 11(a) and (b)). The amount of powder particles present on the no corroded surface contact are most important than that on the corroded discs. This is due to the friability of the corroded surface producing a third body more pulverulent and little adherent powder. Thus, the friction coefficient and the wear rate become lower. The third-bodies, created by the crushing and interfacial pulverization of corrosion scales, could act as solid lubricants [14]. The wear behaviour of the iron oxides depends on their adhesion and their thickness [26]. It is admitted that the friction coefficient and the wear rate decrease when the adhesion of the oxide layer increases and the thickness decreases [27]. The iron oxide represents brightest areas. The traces of corrosion occur much more on the contact of chromium steel surface than the other materials. Since the corrosion layer after exposure of Al MMC A359/SiC_p to the corrosion is too thin and disappears in the first wear test, parallel grooves are formed from abrasion (Fig. 11(c)). That is why, the corrosion layer due to the exposure time has a great influence on the tribological behaviour. Observations on the corroded surface of the chromium steel and the cast iron have shown that after the sliding tests the corroded areas have not been completely eliminated.

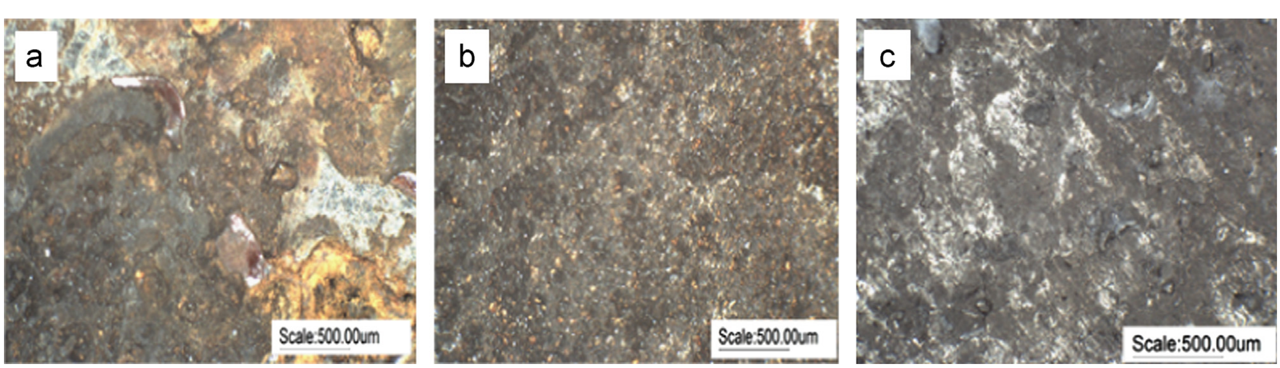

Fig. 9. Surface state of the materials after 6 days of exposure to corrosion: (a) chromium steel, (b) cast iron, (c) Al MMC A359/SiC_p.

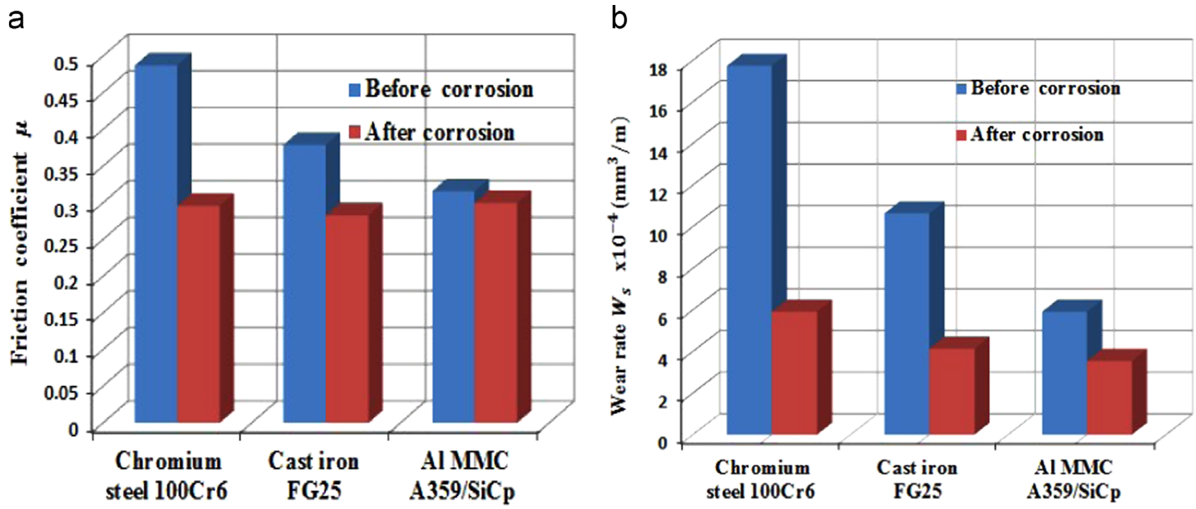

Fig. 10. Influence of corrosion on the friction coefficient (a) and wear rate (b).

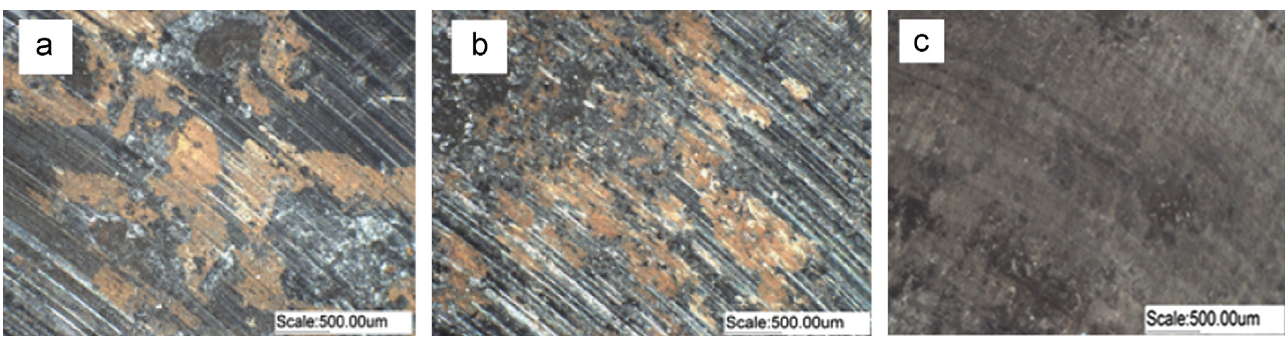

Fig. 11. Micrographs of worn surfaces of the corroded surfaces after sliding test on the tribometer: (a) chromium steel, (b) the cast iron FG25, (c) Al MMC A359/SiC$_p$.

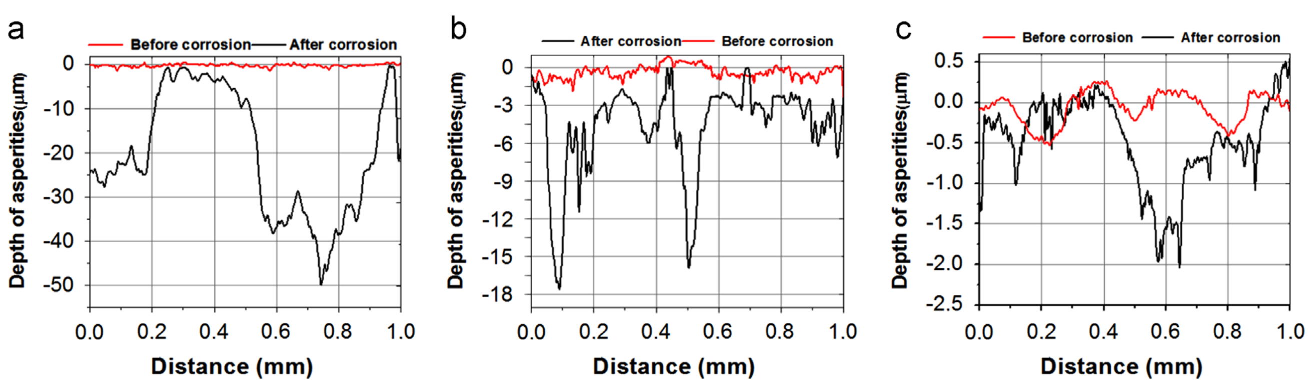

Fig. 12. Surfaces texture of the contact area before and after corrosion during the sliding test: (a) chromium steel, (b) the cast iron FG25, (c) the composite A359/SiC$_p$.

Fig. 12 shows the roughness profile of a portion of the contact area of the discs in cast iron, chromium steel and Al MMC, obtained before and after the corrosion process. The influence of the corrosion on the chromium steel is more important than the other tested materials; this is shown through the frequency of the hollow areas, which are affected by corrosion (Fig. 13). The Al MMC A359/SiC$_p$ is less affected by the corrosion than the cast iron and the chromium steel.

4. Conclusions

The current work aims to evaluate and investigate the tribological properties of three brake disc materials, cast iron (FG25), chromium steel (100Cr6) and the aluminium metal matrix composites Al MMC (A359/SiC$_p$), sliding against one selected commercial resin-based brake pads material, under the influence of normal load, sliding speed, humidity and corrosion due to the salt spray. The evaluation of this study is summarized as follows:

1. An increase in applied normal load reduced the friction coefficient of both brake disc materials (cast iron and chromium steel), also significantly increased their wear rate. For Al MMC A359/SiC$_p$, a stable friction coefficient values were observed and the wear rate followed the same behaviour law that the other two examined materials followed.
2. For cast iron and chromium steel, the friction coefficient increased rapidly up to a certain speed, and then it began to

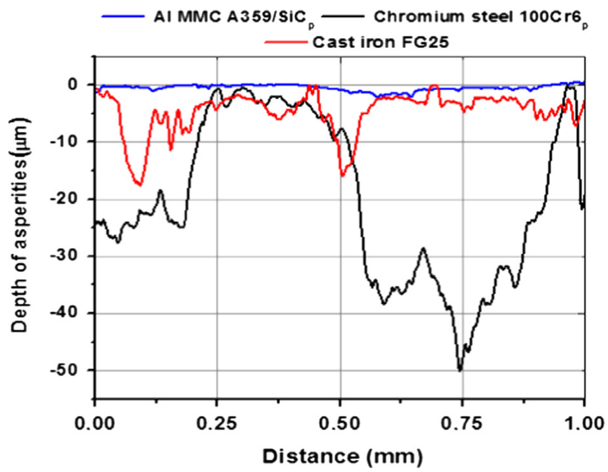

Fig. 13. Comparison between the textures of all materials tested after corrosion process.

decrease. Concerning the Al MMC A359/SiC$_p$, it increased with increasing sliding speed. The wear rate trend was the same for all brake disc materials.

3. The effect of relative humidity on the friction coefficient depended on the tested material. For the cast iron, the friction coefficient increased in the range of low relative humidity (up to 40%), while in the interval between 40% and 90% it decreased. Concerning the chromium steel, the friction coefficient decreased with increasing relative humidity. It noticed that the humidity has no influence on the friction coefficient of Al A359/SiC$_p$.
4. At increased humidity level, a water film formed and behaved as a lubricant; however, the wear rate varied inversely with the relative humidity.
5. The corrosion layer due to the salt spray has a larger influence on the friction coefficient and the wear rate of the cast iron and the chromium steel. Whereas, for the Al MMC A359/SiC$_p$, the corrosion has no influence on the frictional behaviour. This is due to the negligible thickness of the corrosion layer.
6. The Al MMC A359/SiC$_p$ exhibited a better tribological behaviour than the other brake disc materials used in this research under the given test conditions.

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