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Impact of brass contents on thermal, friction and wear properties of brake linings composites

Amira Sellami[1,*], Mohamed Kchaou[1], Reçai Kus[2], Jamal Fajoui[3], Riadh Elleuch[1], and Frédéric Jacquemin[3]

[1] University Sfax, LASEM, National Engineering School of Sfax, B.P. W3038, Sfax, Tunisia
[2] Selcuk University, Technology Faculty Konya, Turkey
[3] Research Institute in Civil and Mechanical Engineering (GeM) (UMR,CNRS 6183), 58 street Michel Ange, BP 420, 44606 Saint-Nazaire Cedex, France

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Abstract. Automotive brake lining materials are composite materials of very complex formulation, highly heterogeneous. They help to carry out the desired combination of braking performance properties. Obviously, it requires that the friction material exhibits a good complementarities and adequate combination of physico-chemical, thermal properties that act synergistically to provide the braking performance which should be adjusted by the addition of metallic fillers. The aim of this work is to study the role of one of the copper alloy particles, namely brass, on friction and wear. For this purpose, the experimental approach is based on the development of a simplified formulation. Three derived composites were developed in the laboratory by the addition 1.5 wt.%, 3 wt.% and 4.5 wt.% of brass. It is shown that addition of copper alloy particles increased thermal properties. Wear test results show that brass contributes to friction and wear mechanisms from a quantity introduced in the formulation equal to 4.5 wt.%. In fact, given its large size, it acts as primary plates serving as supports for the formation and expansion of plates necessary to enhance the stability of friction coefficient. Conversely, when adding an amount less than 4.5%, brass particles are generally all removed from the matrix implying a higher source flow of third-body wear.

Keywords: Copper alloy particles / thermal properties / braking performance / friction mechanisms / wear

1 Introduction

The brake lining material is an organic matrix composite, in which each component provides a well-defined functionality which confers to the material several physic-chemical, mechanical, and thermal properties. These properties together interact in order to provide better braking performance [1,2]. In fact, the organic matrix composite typically contains a binder that holds all components because of its good heat resistance [3]. Furthermore, fillers such as ($BaSO_4$) induce cost reduction of the brake lining materials while being neutral in relation to the friction. However, some studies show that they act indirectly on the tribological behavior of the packing by changing the physical and mechanical properties [4]. Frictional additives are added such as rubber to control the dynamic behavior of the material due to its damping capacity. It provides elasticity to the material allowing a greater contact with the rotor and a better distribution of forces applied to the surface. This improves the stability of friction. Solid lubricant typically graphite promotes the stability of the friction at high temperature and makes it less sensitive to the sliding speed [5,6]. Abrasive particles (Al_2O_3, SiO_2) enhance friction performance. Several metallic elements such as copper, steel and brass have been incorporated in the formulation of brake lining materials to assign, by their morphology and properties, the thermal and tribological behavior [7].

This variability of the formulation complicates the understanding of tribological behavior and the role of each component [8]. Indeed, because of the influence of ingredients on the friction and wear mechanisms [9,10], it is crucial to understand the link between the development of friction materials and braking performance [11]. To overcome the complexity of industrial formulations which is an obstacle to the analysis of the role of the components in the braking, the study is carried out with simplified formulations composed of a reduced number of constituents. The challenge is to limit the heterogeneity of the material and simplify its micro-structure to facilitate identifying and understanding the role of specific components.

In addition, the metallic components are important in friction materials since they control the thermal properties of organic matrix composites apart from additional functions

* e-mail: amira_sellami@hotmail.com

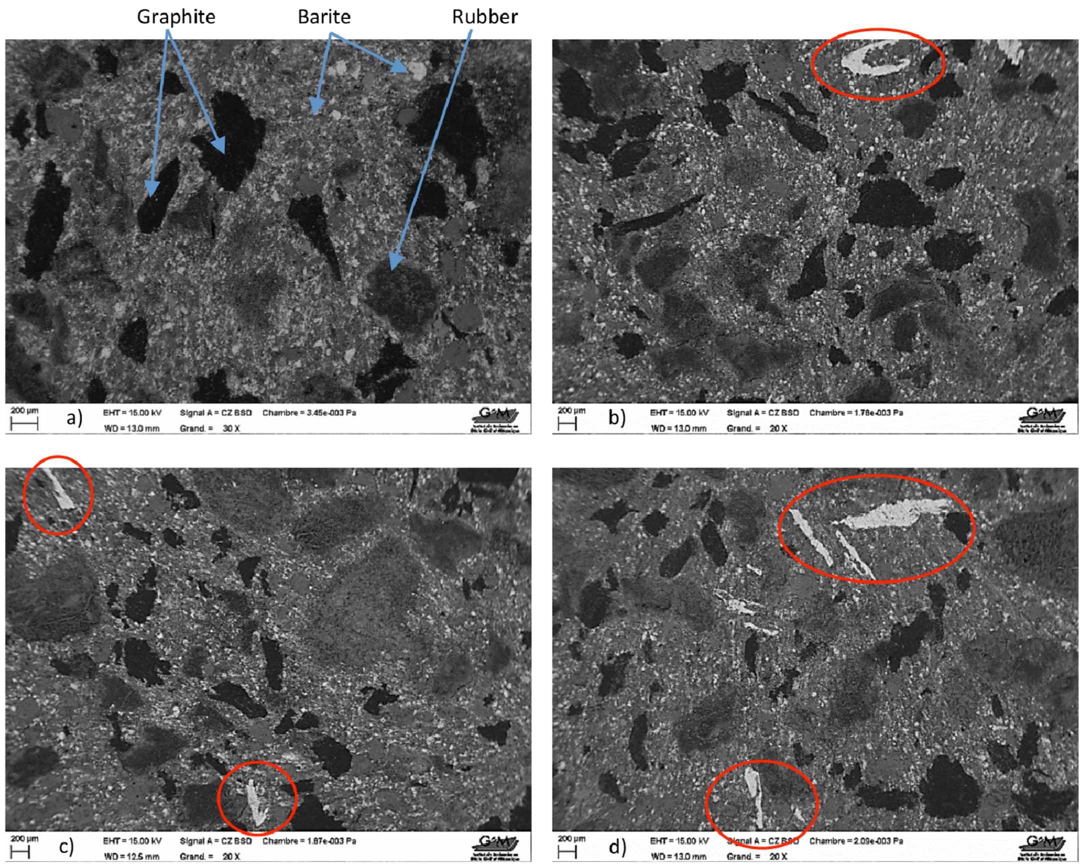

Fig. 1. SEM observations of the friction materials, (a) M, (b) M1.5, (c) M3, (d) M4.5 (copper alloy particles indicated by red arrows).

Table 1. Studied brake linings compositions (wt.%) (reference and derived formulations).

Classification	Component	M	M1	M2	M3
Binder	Phenolic resin	14	14	14	14
Filler	Barite	45	43.5	42	40.5
Fiber	Rockwool	22	22	22	22
Particule	Brass	–	1.5	3	4.5
Lubricant	Graphite	10	10	10	10
Friction modifier	Rubber	7	7	7	7
Abrasive	Alumina	2	2	2	2

such as friction. Few publications deal with the role of metallic fibers in brake lining materials [12]. Recently, researchers confirm that friction composite which contains 8% brass fibers proved to render a good combination of tribological and thermal performance [13]. Kumar reports that brass fiber not only improves properties of the brake lining material but plays also an important role to improve the tribo-performance at the scale of the interface pad-disc while avoiding the aggressiveness against the rubbed area [14]. Actually, researchers are studying the size and the shape of brass and how they affect the properties of the material: they confirm that powdery metallic fillers improve better braking performance than fibrous [15].

In the present study, derived from the simplified formulation, new formulations have been developed by introducing brass. It is added by substituting the equivalent in weight percent of barite. Since the thermal conductivity affects the dissipation of the frictional especially for a brake inducing high temperature levels, tribo-evaluation tests were conducted under moderated solicitation. Scanning electron microscopy (SEM) and EDX analysis were done to identify and understand the friction mechanisms at the pad-disc contact.

2 Materials and methodology

2.1 Brake lining formulations

To overcome the complexity of composite formulations, simplified formulation is developed and used as a reference “M”. The composition of the laboratory formulation is given in Table 1. The challenge is to simplify the tribological

Table 2. Physical and thermo-physical properties of the studied friction materials (the standard deviation and the number of tests are indicated in parentheses).

Properties	M	M1.5	M3	M4.5
Density (g/cm^3)	2.17	2.2	2.23	2.25
Specific heat (J/kg K)	673 (4.1/5)	793 (3.9/5)	824 (4.2/5)	854 (4.4/5)
Thermal conductivity (W/m K)	1.04 (0.01/5)	1.31 (0.08/5)	1.38 (0.06/5)	1.52 (0.002/5)
Thermal diffusivity (10^{-4} m^2/s)	71	75	76	79

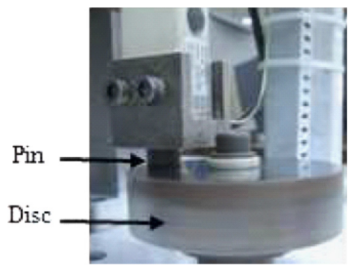

Fig. 2. Pad-on-disc tribometer.

function of the material, to facilitate the study of its properties, its mechanical behavior, with the aim to better understand the action of the components. Derived from the reference "M", the fabrication of three composites was based on adding one of copper alloy particles namely brass particles. The formulations, namely M1.5, M3, and M4.5 contain respectively 1.5, 3 and 4.5 wt.% of copper alloy particles. When substituting the barite by copper alloy particles, an equivalent weight fraction instead of volume fraction is used. This choice is due to the difficulty in selecting fixed volume fraction due to the differences of shape, size, weight and even distribution of both ingredients.

The manufacturing process of the friction material comprises dry mixing, pre-forming, hot molding and post curing. Dry mixtures were done using electric mixer at 2000 rpm for 20 min and pre-formed under a specific pressure of 20 MPa at 150 °C for 18 min. For the post-curing, we used a conventional electrical curing oven at 160 °C for 10 h.

At the end of the manufacturing cycles for the preparation of the brake lining materials finishing operations are required to have a plate having a thickness of 16 mm and a surface area of 400*400 mm^2.

2.2 Morphological characterization

The microstructure of friction materials noted M, M1.5, M3 and M4.5 is observed in the normal direction to the sliding direction by SEM (Fig. 1). Surfaces present strong microstructural heterogeneities (Fig. 1a). They present different components of sizes ranging from the micrometer scale to the millimeter scale. All components were scattered randomly.

Barite appears white with variable size ranging from some micrometers to some hundred micrometers. Graphite is consisted by scattered particles with the largest particle size with respect to other particles with an average size of about 500 μm. Brass is added in the form of machining chips. Its morphology mainly presents large particles in light gray with a length up to 1.5 mm and an average diameter of 300 μm (Fig. 1b). The cohesion between the different components is provided by the phenolic resin. Friction materials with additional copper alloy particles present similar microstructure to the reference with a good distribution of copper alloy particles on the surface (circled on red with interrupted line), Fig. 1b–d.

2.3 Thermo-physical properties

All the studied materials are characterized in terms of physical (density) and thermo-physical properties (thermal conductivity and specific heat). Thermo-physical properties were determined using the hot disk thermal constants analyser.

For the thermal conductivity, measurements are conducted on two samples of 50 mm diameter and 16 mm thick. The sensor is sandwiched between the two sample pieces. For the specific heat, the sample of 14 mm diameter and 4 mm thick is placed in an insulated gold container and carefully heated a few degrees with a well-defined heating effect, allowing very accurate calculation of specific heat. The density of the sample was determined based on Archimedean principle in water according to ASTM D792. Details of measurement procedure of these properties are discussed elsewhere [16].

As indicated in Table 2, it is noteworthy that density of friction materials increases with the addition of metallic particles which are heavier than barite. The thermal conductivity increases from 1.05 W/m K to 1.52 W/m K. Its improvement after copper alloy particles addition is due to the metallic nature of the added particles. The specific heat increases from 673 J/kg K to 854 J/kg K. From these data, diffusivity is calculated: it is higher for M3 compared to the other formulations.

3 Friction and wear test

The tribological behavior of each material is carried out by friction and wear tests achieved on a pad-on-disc tribometer. Pad of size (diameter 14 mm × thickness of 16 mm) was cut from the brake friction material. The pad rubbed on the disc made by grey cast iron (Fig. 2).

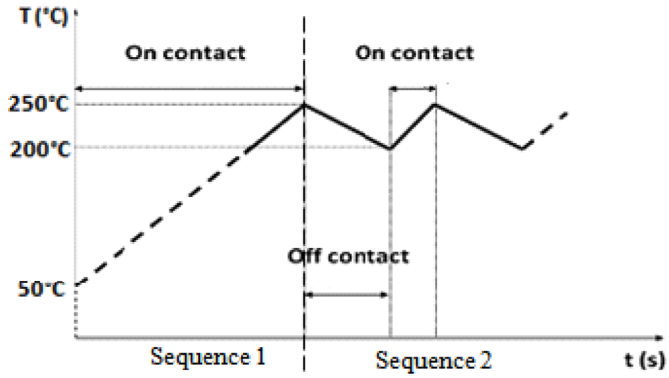

Fig. 3. Experimental protocol.

The brake system is composed of a 0.8 m radius and 0.15 m thick disc. The disc is equipped with K-type thermocouples placed at friction radius under 2 mm of the disc surface. The pad is equipped with K-type thermocouples placed at the pad center above the friction surface.

A new disc is used for each friction test.

All tests were carried out at ambient temperature (without external heating) with a relative humidity between 40% and 50%.

The normal load is imposed on the pad through a pneumatic jack and the rotation speed of the disc is piloted by an electric engine.

The friction coefficient is calculated from the instantaneous values of the normal and tangential loads measured by load sensors. The loss of mass by distance is the parameter chosen to compare the wear resistance of the materials of friction.

The friction test is monitored by the disc temperature operating under moderate thermal load [200–250 °C] (Fig. 3). The test was performed with a constant rotation frequency of 1785 tr/min and a normal load of 185 N. These conditions were defined as representative of on road braking at medium dissipated energy [9,10]. Before the beginning of the wear test, a running-in phase is performed, defined as several low-temperature friction cycles with a rotation frequency of 895 tr/min, a normal load of 92 N and a disc temperature range from 70 to 100 °C. The running-in phase ends when the surface of the pad is almost totally rubbed. The friction test program comprises two sequences controlled by the disc temperature.

– Sequence 1: consists of rubbing the pad against the disc until its temperature, down to 2 mm from the friction surface, increases from an initial temperature 50–250 °C.
– Sequence 2: consists in successive cycles of “On and Off contact” with a rotation frequency of 1785 tr/min and a normal load of 185 N. After sequence 1, the load is removed and the disc is cooled with free rotation up to 200 °C. This period is defined as “Off contact”, thus the first cycle is finished. Then, the load is again applied and the continuous braking is done until the disk temperature reached 250 °C. This period is defined as “On contact”. At this moment, pad and disc are separated and the disc is cooled again up to 200 °C. So, a second cycle is achieved.

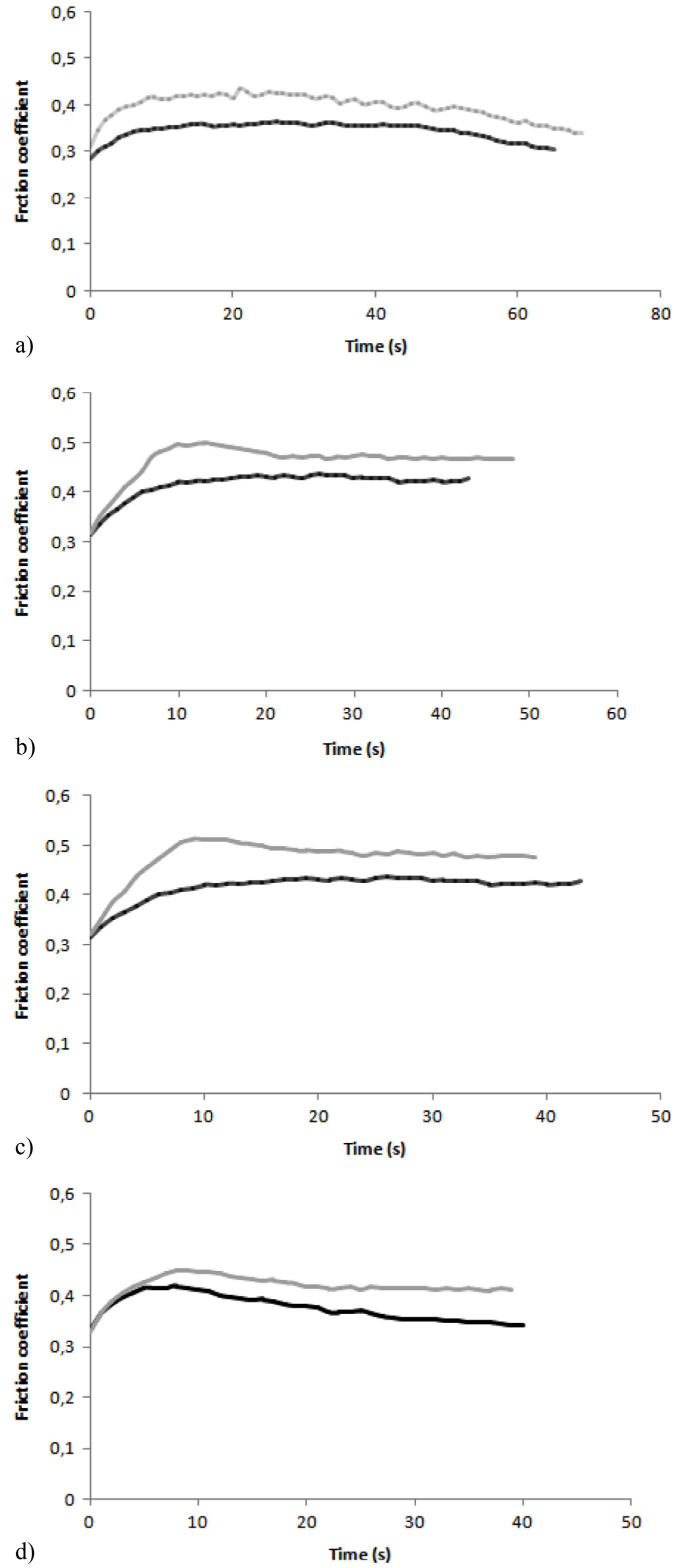

Fig. 4. Min (black) and max (grey) friction coefficient evolutions: (a) M, (b) M1.5, (c) M3 and (d) M4.5.

The test ends when the friction distance is equal to 15 km.

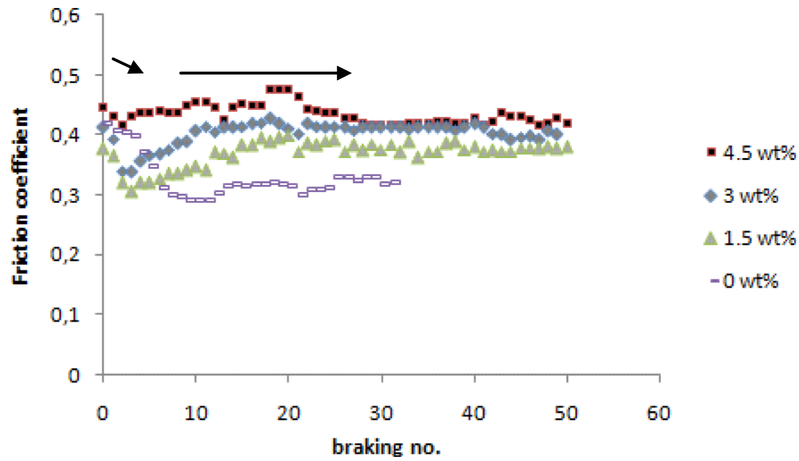

Fig. 5. Average of friction coefficient under braking number.

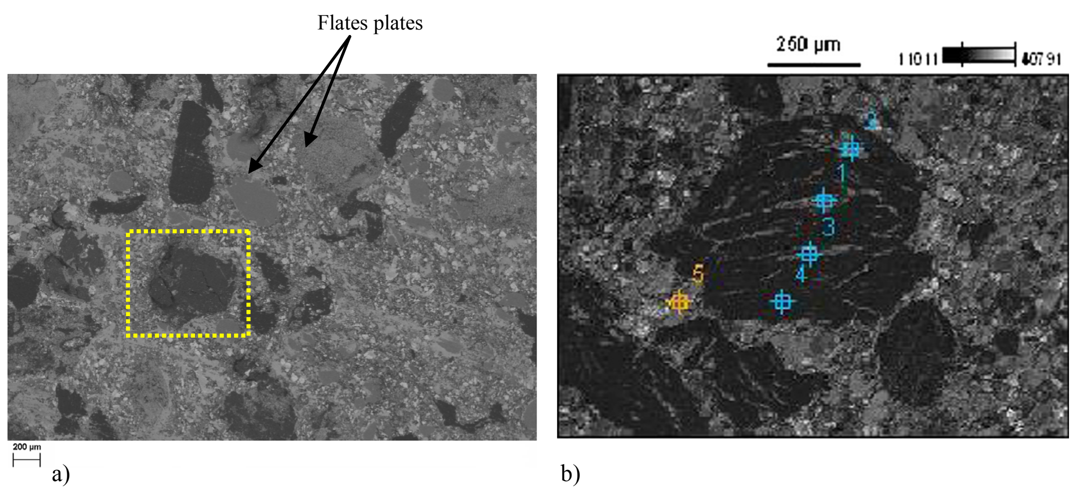

Fig. 6. (a) SEM of the rubbed surface of the material "M", (b) Detail Z1 and EDX localized zones (accelerating voltage: 15 kV, the arrow indicates the sliding direction).

4 Results and discussion

4.1 Effect of copper alloy particles on frictional behavior

The results of the wear test carried out on the tribometer are depicted in the figures as curves giving the friction coefficient μ versus the duration of the friction cycle.

All friction cycles are recorded between two friction levels: minimum ($\mu_{\min}$) and maximum ($\mu_{\max}$). In fact, $\mu_{\min}$ and $\mu_{\max}$ represent, respectively, the lowest and the highest coefficient of friction for each test.

Figure 4 shows the $\mu_{\min}$ and the $\mu_{\max}$ of each friction material. It's obvious that the evolution of friction coefficient from a cycle to another is more regular for composites M4.5. It seems that all friction materials show μ in the same range (0.4). Likewise, we note that the time required for the disk temperature to reach 250 °C, decreases by adding brass which is caused by the higher thermal conductivity of the formulation containing copper alloy particles. Indeed, an increase in thermal conductivity allowed a fast increase in temperature followed by dissipation of this heat by conduction through the pad.

It can be inferred that the content of brass more than 4.5 wt.% affects the frictional performance of the composite by increasing the stability of friction.

Figure 5 shows the evolution of average friction based on the braking number. We note that the friction coefficient decreases from the first to 4th cycles for composites with 1.5 wt.% and 3% of brass, and from the first to third cycles for composites with a percentage of brass equal to 4.5 wt.%. In contrast for the reference formulation, friction coefficient decreases since 8th cycle from 0.42 to 0.3. According to Kumar, the significant decrease of the friction performance is attributed to the formation of a glaze sticking to the disc. This phenomenon responsible of deterioration of braking efficiency is called "fade" [17]. Regarding our results, the decrease of the slope with the addition of brass reflects fade resistance. In fact, due to the higher thermal conductivity of copper alloy, there is dissipation of the frictional heat generated on the counterface.

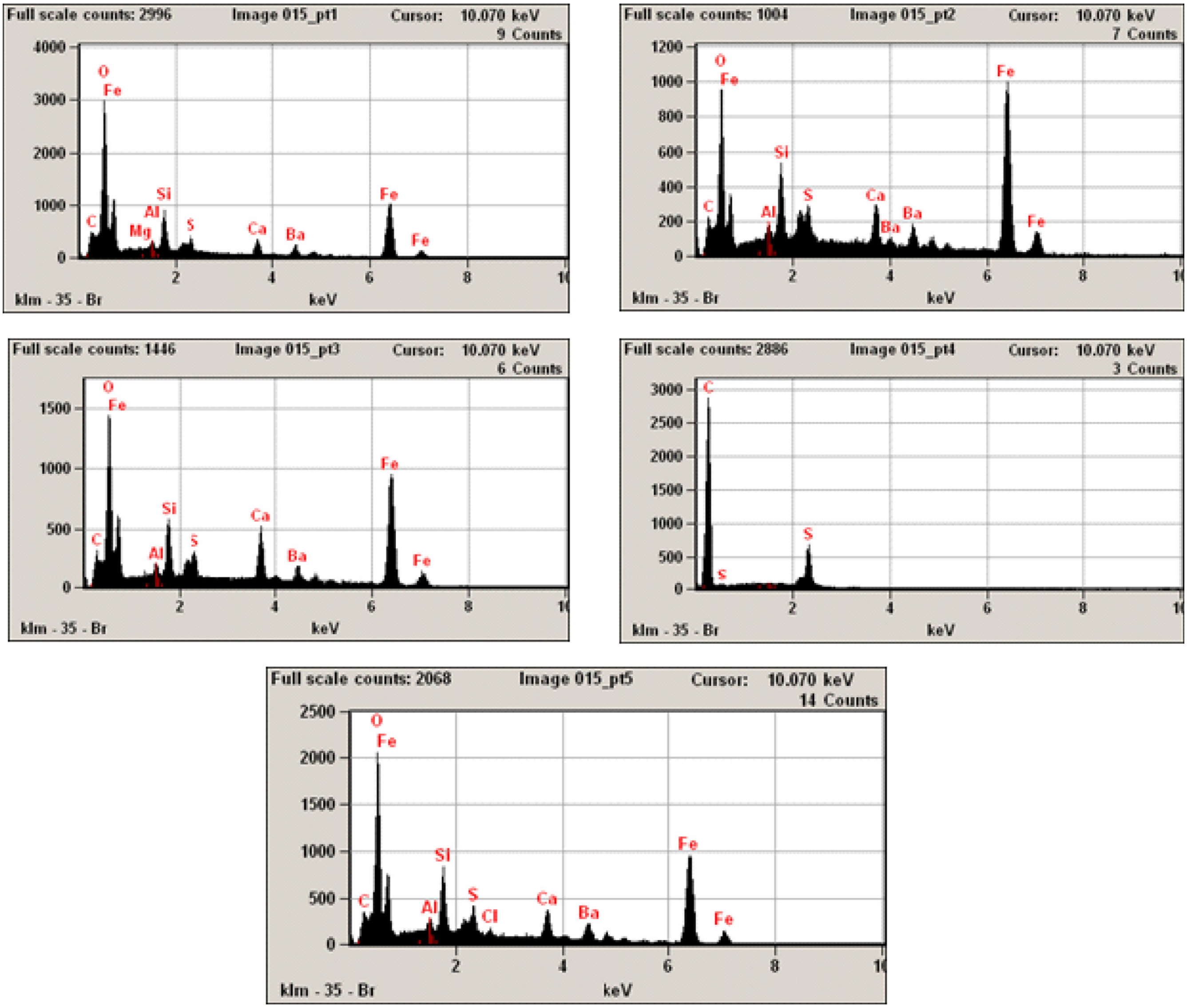

Fig. 7. EDS results of localized zone in Figure 6b.

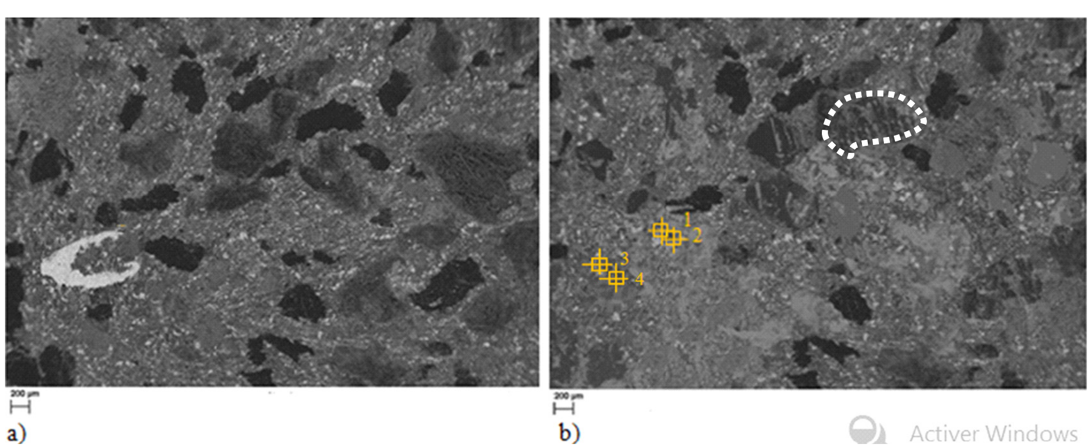

Fig. 8. SEM of the pad of material M1.5, (a) before friction test, (b) after friction test.

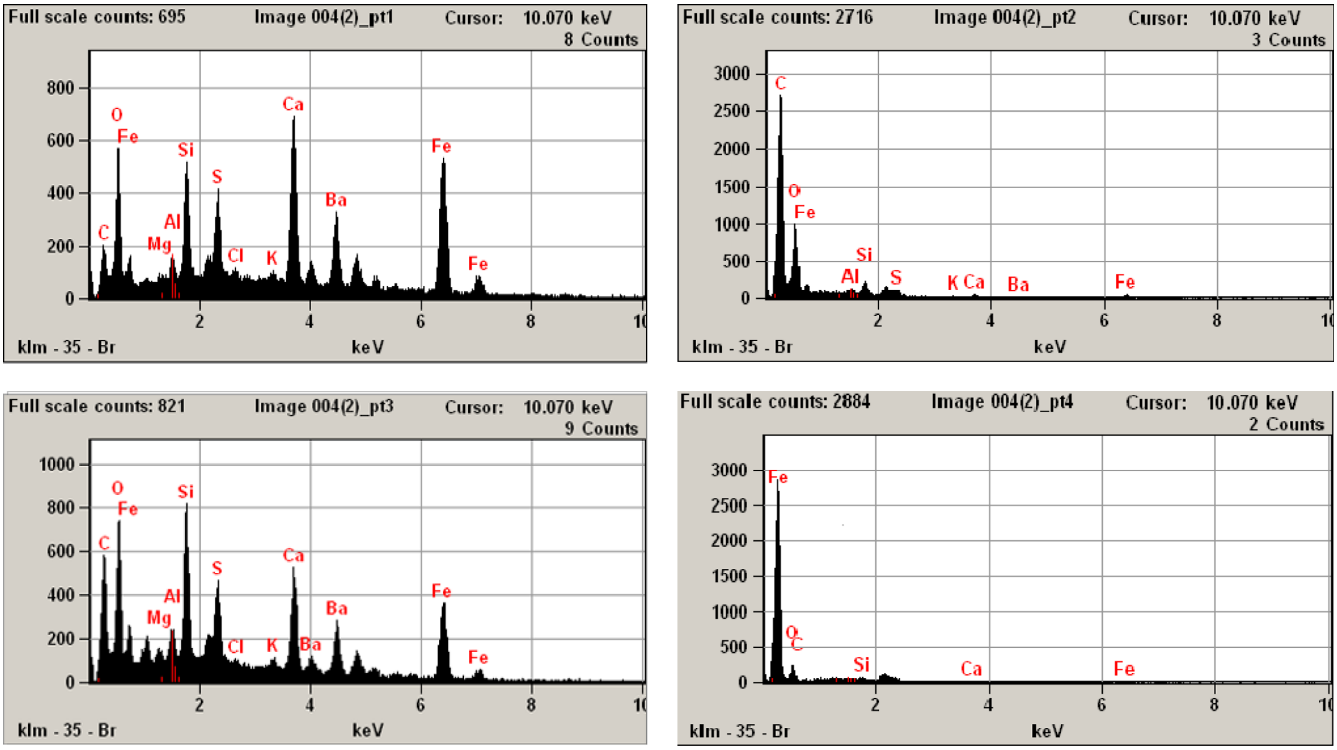

Fig. 9. EDX analysis of zone located in Figure 8b.

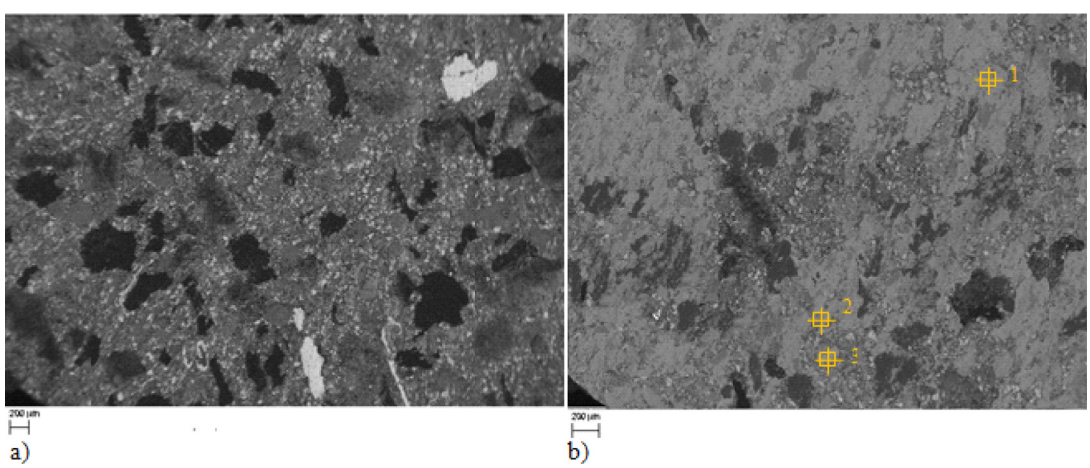

Fig. 10. SEM of the pad of material M3, (a) before friction test, (b) after friction test.

4.2 Effect of copper alloy particles on friction and wear mechanisms

Figure 6 presents the SEM observations made on rubbed surfaces of friction surface M. A smooth surface is noticed, covered by multilayer third body which is beneficial for the protection of the friction surface from the pronounced wear rate at 250 °C. Although, we found that the third body is extended in the form of secondary plates bearing the load. Indeed, they comes from the accumulation and compaction of the third body trapped on the "plate" formed by the primary constituent elements of the friction material. The coalescence of adjacent flat plates, leads to an increase in sizes that may reach several millimeters. In fact, they serve as bearing surface necessary in the development of secondary plates. The majority of particles, which appear dark grey, are rich in carbon (Fig. 6a). It does not seem to be affected by the friction and wear mechanisms. These particles do not form preferentially supports of the secondary plate development. The EDX analysis (point 4) is in good agreement with the SEM results since there is a large peak of element C. In other surface regions (points 1, 2, 3 and 5), the material components are almost covered by a thin third body layer. The EDX analysis reveals the presence of all the characteristic elements of the third-body (Fig. 7).

SEM analysis of the pad rubbed area of material M1 (Fig. 8b) shows that rubber is often fragmented and detached, forming imprints on the surface (circled with

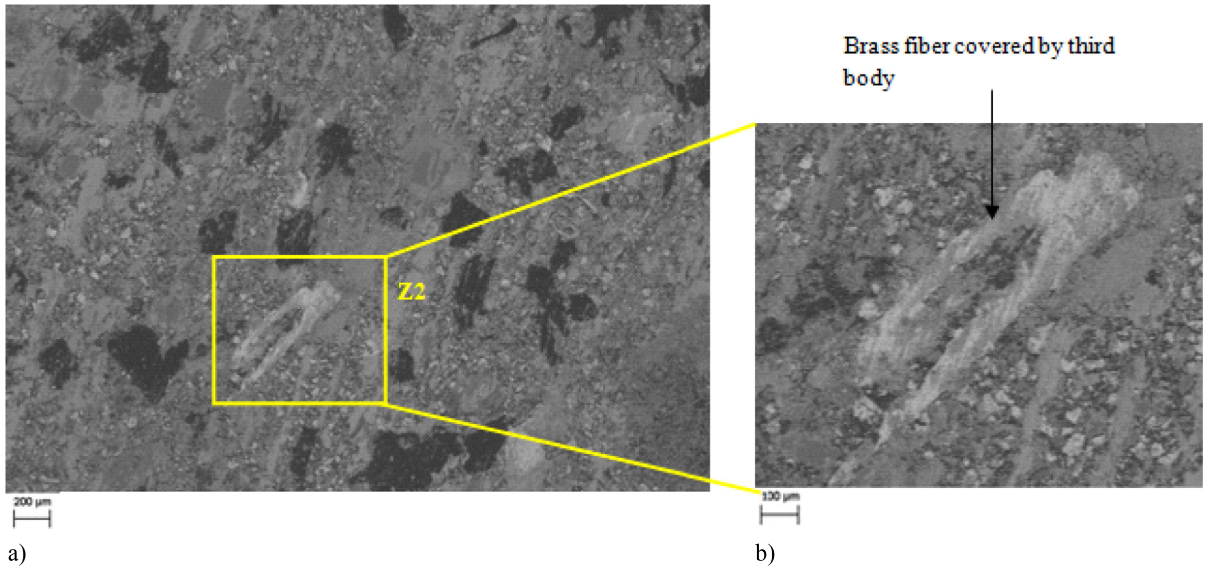

Fig. 11. (a) SEM observations of the rubbed surface of M4.5, (b) Details Z1.

Table 3. Chemical analysis of zones located in Figure 9b by EDX.

	C	O	Na	Mg	Al	Si	S	K	Ca	Fe	Ba
1	20.78	45.46	0.50	–	8.83	18.21	–	3.58	–	0.18	2.46
2	25.99	41.08	–	0.29	0.98	3.06	10.45	–	1.61	11.44	5.10
3	29.89	37.16	–	–	1.07	5.53	2.16	0.12	3.56	17.73	2.79

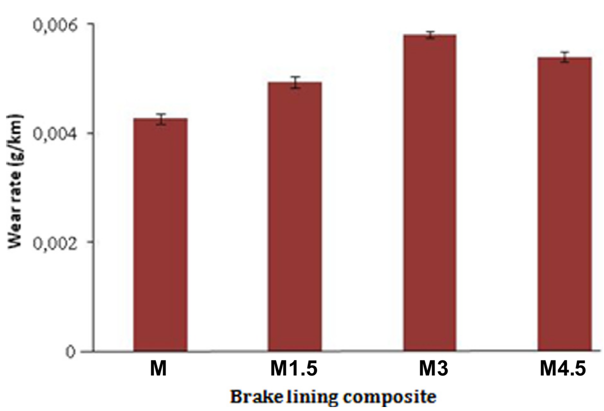

Fig. 12. Wear rate of the friction materials M, M1.5, M3 and M4.5.

interrupted red line). It seems to be the more degraded component. The rubbed area of the pad has a surface area similar for each formulation. Indeed, the flat plates develop on the mineral fibers and extend externally by compacting powder accumulated against them.

In order to follow the role of the brass in the wear mechanisms, the zone of the brass particle, identified before friction test, was subjected to focus X-EDS analysis at different points after friction test (Fig. 9). EDX spectrum shows peaks characteristics of the third-body composition with elements originating from the pad and the disc with the absence of the characteristic elements of brass (Cu and Zn). Regarding the material M3.5, Figure 10 presents the pad surface before and after the friction test and the localization of the X-EDS analyses. The analysis performed in a brass particle zone (recognized by its color and form before the test) shows the absence of elements constituents of brass Table 3. On other hand, the rubbed surface of the material M4.5 (Fig. 11) shows the presence of brass particle covered by third body: it is trapped and accumulated against copper alloy particles that play the role of obstacle, and then favour the formation of more developed flat plates. It acts as primary plates which form supports for the secondary plates to develop.

The comparison between the wear mechanisms induced by friction, having a mass quantity of copper alloy fiber less than 4.5% (M1.5 and M3), shows the absence of copper alloy elements on the rubbed surface. However, for M4.5 (4.5 wt.%), brass particles still remain in the contact after running the friction test. In fact, given its large size, copper alloy particles are removed and did not contribute on wear mechanisms. So, when the mass quantity of copper alloy used in the formulation of the pad is high enough that even with the quick release of copper alloy particles, some particles remain attached to the matrix and contribute to the mechanisms of formation and expansion of third body. The amount of copper alloy particles added to the formulation M4.5 (4.5 wt.%), is sufficient to contribute to wear and friction mechanisms.

4.3 Effect of copper alloy particles on wear

Results show that the friction material M (without copper alloy particles) has a lower wear rate than the other composites (Fig. 12). In fact, by increasing the amount of copper alloy particles, until 3%, wear increases. As we have already shown, in holding the large copper alloy particles, they are quickly pulled out of the matrix and ejected out of contact. This behavior causes a loss of mass that increases proportionally with the amount of copper alloy particles incorporated. However, in the case of the composite M4.5, copper alloy particles remain anchored to the matrix and contribute to the mechanisms of friction which causes a mass loss of less than composite M3.

5 Conclusion

Based on the experimental study, conducted in a perspective to investigate the impact of adding the brass at low mass percents on friction and wear mechanisms, the following conclusions are quoted below.

– The addition of brass particles in the formulation of the brake pad material affects the thermal properties in a beneficial way. Density, thermal conductivity and thermal diffusivity increased with copper alloy contents.
– Frictional responses of the studied materials showed similar trends of $\mu_{\min}$ and $\mu_{\max}$ up to 3 wt.% copper alloys particles, except that for the material containing 4.5 wt. % of brass shows more stable level of friction.
– The organic matrix composites having more brass in their formulations can dissipate more heat generated by friction leading a higher fade resistance.
– The overheating of the rubbed surface of the pad (250 °C) deteriorates the bonding between components and hence leads to easy elimination of copper alloy element.
– Rubbing surface investigations coupled to the EDX analysis showed that 4.5 wt.% of brass in the formulation of the brake pad is enough that even with the release of copper alloy particles, some particles remain attached to the matrix and contribute to the mechanisms of formation and expansion of third body which explain the stability of the friction coefficient for the material M4.5.
– Under sliding, rubbed surface inspection shows excessive delamination of copper alloy particles, which explains the high wear of composites with 1.5 wt.% and 3 wt.%. Thus increase in copper alloy content more than an amount of 4.5 wt.% led to their contribution on wear mechanisms and it remains present on the rubbed surface of the pad.

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