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Structural and Tribological Analysis of Brake Disc–Pad Pair Material for Cars

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Abstract: The study of the tribological behavior of the braking system in auto vehicles requires knowing the characteristics of the material in contact and, in the work process, the friction pair brake disc pads. Material structural analysis is necessary because the wear process depends both on the friction-pair chemical composition (brake disc pads) and on the work process parameters (pressing force, rotational speed, traffic conditions, etc.). The material of the brake discs is generally the same, gray cast iron, and the brake pads can be semimetallic (particles of steel, copper, brass, and graphite, all united with a special resin), organic materials (particles of rubber, glass, and Kevlar, all joined with the help of a resin), composite materials that contain different constituents, and ceramic materials (rarely have small copper particles). Therefore, the purpose of this paper is to analyze the crystalline structure, tribological behavior (at friction and wear), and the mechanical properties of the materials of the brake disc–pad friction pair specific to the field through study and analysis.

Keywords: brake pads; crystalline structure; tribological properties; brake disc–pads

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1. Introduction

Evolution over time of braking systems has meant yielded continuous improvement in efficiency and reliability [1]. The main function of the brake is speed control, and the deceleration rate of a vehicle is defined by energy dissipation.

The main objective of the braking system study is to improve its performance to ensure safe, stable braking in any situations/conditions. This improvement is brought about by the structural changes in the materials of the disc-brake pad pair due to the problems that appear in the braking system (creak, noise, and vibrations).

These problems can be solved by decreasing the friction coefficient (COF), but this also decreases the performance of the braking system [2]. These factors encountered in the braking system are a problem for the automotive industry and for passengers, being essential in the design stage of a braking system.

Studies have considered different parameters, such as the coefficient of friction and other constructive parameters of the braking system. To avoid as much as possible the problems of creaks, noise, and vibrations, these parameters assume structural modifications in the brake disc–pad pair. Due to the influence of structural changes, this is necessary information for the optimal choice of friction-pair materials to ensure the performance and stability of the braking system [3].

Based on previous experience, it is necessary to develop new friction materials and test their characteristics not to repeat the same shortcomings in their structure, but to obtain total quality and reliability [4].

Many numerical simulations have been performed for the contact interface (friction) of the disc material and brake pads, considering their predominant influence. At present, these contacts influence the phenomena of noise, creak, and vibrations, and therefore stability is not yet well understood [5–8]. Therefore, braking system performance represents one aspect of improving friction material properties, in particular those of the contact surfaces.

Thus, the brake screeching phenomenon was analyzed by Ganji and Ganji [6,9], considering the motion of nonlinear equations due to large deformations and the revision of different material selection schemes, to find an optimized selection procedure [10]. Phatak and Kulkarni [11] achieved squeal reduction by structural modification and by studying the parameters affecting brake noise.

For a good understanding and prediction of the tendency of squealing in automotive brake systems, researchers have proposed complicated models with multiple degrees of freedom.

Shin et al. [12,13] simplified the physical model into a two-degrees-of-freedom system model coupled with a disc–disc friction pair and found periodic and chaotic vibrations in the system. Paliwal et al. [14] considered the coupling stiffness between the disc and pad interface based on Shin's model and studied the impact of the coupling stiffness on the stability and anti-skid vibration of the braking system.

Shen [15] realized and tested brake pads with three layers, the first and third layers being made of plastic and the middle layer of felt. Such pads reduce noise, improve the impact resistance of the brake pads, and ensure braking system stability. Gao and Song [16] proposed friction material for brake pads to be obtained by the process of metal-based sintering because it improves adhesion, COF, and wear resistance. This transformation supposes that structural changes can create brake pads with varying stiffness and damping.

This process can improve the braking system stability and reduce noise and vibration when braking, but its dynamics remain unclear. Instead, Wei, et al. [17] proposed braking pads with two layers (one basic and another friction) by simplifying the three-layer ones.

To produce braking force, the friction layer is in contact with the brake disc, while the base layer plays the role of support. By optimizing the brake pad parameters, the chaotic vibrations are reduced [18], and hence the braking system stability is improved.

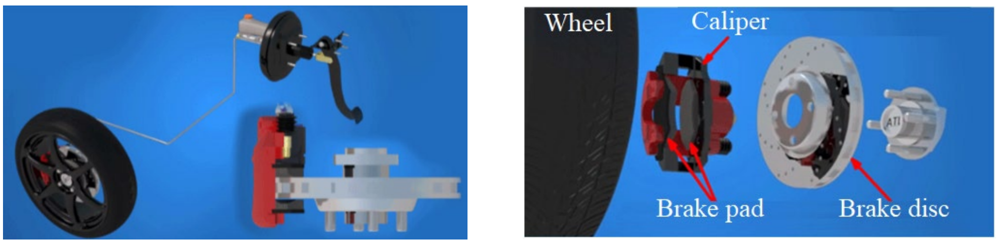
Experiments on the wear behavior of brake pads must be preceded by metallography [11,12], chemical [16], and even mechanical analyses [17,18] of the materials in contact. The wear process depends on both the brake pad material and the disc material together with the working process parameters (pressing force, traffic conditions, rotational speed, etc.).

These analyses are necessary because the wear process does not depend only on the brake pad material but also the disc material and the working process parameters.

Therefore, the aim of this paper is to undertake structural analysis (metallographic, chemical, but also mechanical) of used materials as well as their tribology, particularly those on contact surfaces (before experimental testing at wear) to obtain the experimental data necessary to improve the braking system, to extend its life, and optimize its operation.

2. Materials and Methods

The main purpose of braking systems is to achieve the required braking torque, which causes the wheels to slow down and therefore brake. Today, most cars are equipped with the brake disc–pad system (Figure 1a) on both the front axle and the rear axle.



(**a**) (**b**)

Figure 1. Assembly braking system (**a**) with the component elements (**b**).

The braking system is a rotating cast iron disc rotated by the wheel hub and a bridge element, called a caliper, which is fixed on the axle housing, hub axle, or suspension bracket depending on the particular version, and it rides on the disc (Figure 1b). The caliper contains a of pistons and the brake pad pair, which by pressing the brake pedal locks the rotating disc, depending on the generated hydraulic pressure behind each piston, and determines the speed reduction [19–21].

First, the samples were taken and prepared to perform the metallographic, chemical, and mechanical analyses in according with [19,22]. Using a metallographic microscope (Olympus NTD Inc., Boston Industries, Inc., Boston, MA, USA) equipped with a camera and image processing software Stream Essentials, the metallographic analysis was possible on samples taken from the brake pad shown in Figure 2.

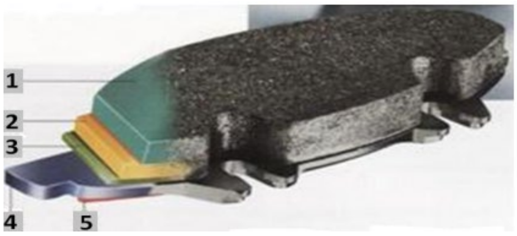


Figure 2. Brake pad: 1. friction material; 2. intermediate layer; 3. adhesive; 4. main frame; 5. damping layer.

For this, brake pad samples were sectioned using a Bosch Multi Wheel cutting machine with a disc of 76 × 10 × 1 mm manual actuation (Struers Inc., Struers LLC, Cleveland, OH, USA).

The samples from the brake pad and disc to be analyzed by microscopy were introduced in a resin matrix with a hardener and mixed in a special bowl. During mixing, a thin resin film is deposited on the material sample surface (from the analyzed brake pads, Figure 3). For optimal conditions, microscopic analysis was necessary to remove the resin film (Figure 4) by sanding and polishing, with the help of a Tegramin 25 (Struers Inc., Struers LLC, Cleveland, OH, USA).

Figure 3. Resin film over brake pad analysis area.

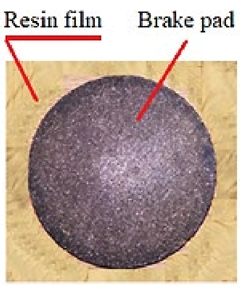


Figure 4. Removal of the resin layer.

Then, this machine (using the predefined program from the database) was used for grinding and polishing the metallic sample material from the brake pad (Figure 4), respectively, of the sample from the brake disc material (Figure 5).

Figure 5. Brake disc sample polishing.

The final stage of sample preparation is metallographic attack, which has the role of highlighting the crystalline structure [22,23] of the brake pad material for metallographic analysis. Thus, to make the crystalline structure components, the sample's polished surface is cleaned by washing with water, followed by drying and attack with reagents, which dissolve or color them.

For reliable chemical characterization, energy-dispersive X-ray spectroscopy (EDS) elemental mapping is an analytical technique that allows materials' elemental chemical analysis/characterization. To provoke X-ray emission, the sample is excited by an energy source (for example, an electron microscope electron beam), and some of the absorbed energy is dissipated by ejecting core–shell electrons.

Information regarding chemical composition can be obtained down to the atomic level by an EDS detector addition of to the electron microscope. Then, a higher-energy electron from the outer shell continues to fill its place, releasing in the form of an X-ray, a difference in energy, and a characteristic spectrum of its atom of origin. This allows composition analysis of a sample volume, given that has been excited by the energy source. Because characteristic X-rays are emitted and measured while the electron beam is scanned across the sample, each EDS spectrum is recorded and mapped to a specific position on the sample. Thus, the signal intensity corresponds to the element concentration, whereas the position of the peak in the spectrum identifies the element that will be seen in the next section.

The resulting quality depends on the signal strength and the spectrum clean. While signal strength allows particularly trace element detection and dose minimization and is based on a good signal-to-noise ratio, the cleanliness will affect the number of spurious peaks as a result of the materials that make up the electron beam.

The EDS spectrometer determines the material elemental composition, identifies the substance components, and quantifies the element's present amount [24].

Normally, the discs of vehicles are made of gray cast iron and the brake pads of composite materials. The composite materials contain different constituents (sometimes 10 or more) and are compacted into a solid mass with a porosity of 5–10% by hot pressing [25]. Although these composite friction materials have a wide variety of compositions, constituents can be broadly classified according to Table 1, together with a short summary of the functions of each constituent and some examples.

Composite materials are made by combining at least two constituents on a macroscopic scale. The mechanical and chemical bonds that appear between the matrix and reinforcement of the composite give rise to a material whose properties are superior to the constituents taken separately. For this reason, the properties of composite materials are influenced by those of the constituent materials, by the volume fraction of the reinforcing component, by the orientation of the reinforcement in the composite, etc. [23].

Table 1. Component elements of brake pads.

Constituents/Description	Function	Examples
Binder	Form thermally stable matrix	Thermosetting phenolic resin
Fibers	Provide mechanical strength	Brass, steel, Kevlar, glass, ceramic
Lubricant	Stabilizes friction, especially at high temperatures	Graphite, metal sulfides
Abrasive	Increases friction, cleans the surface film on the disc	Alumina, zirconium, metal silicates, chromium oxide
Filler	Improves manufacturing and reduces cost	Barium sulfate, mica, vermiculite

The type of cast iron (with graphite flakes or spheres etc.), together with the metallographic composition, are very important because small or large amounts of other elements (titanium or vanadium) strongly influence the performance at friction and wear or make it unusable [26].

For tribological analysis of the composite materials with metallic constituents, depending on some parameters of the work process, a pin-on-disc tribometer was used. A gray cast iron ventilated brake disc with a diameter of 260 mm and a thickness of 22 mm was used as a disc, attached to the tribometer disc which can rotate at different speeds (in the case of the front 10, 12.5, and 15 m/s). The pin was a cylindrical sample taken from a brake pad (made of ceramic metal material) with a diameter of 10 mm and a height of 10 mm, fixed in the arm of the tribometer and pressed on the disc with different loads (in the case of the front 2, 3, and 4 MPa). The same operating conditions were used for at least three replicates, for a closer and more correct to check and assess the experimental results.

Therefore, the methodology involves structural, tribological, metallographic, and chemical analysis of samples taken from a brake pad (see Figure 2) and the disc on a vehicle (car, see Figure 1)as follows.

3. Results and Discussion

The sliding contacts between the friction material of the pads and the brake discs decelerate the vehicle by dissipating its kinetic energy, which slows the movement of the wheels. The slip between the disc and the brake pads is about half the vehicle speed. At the same time, the real contact area is typically between 15% and 20% of the pad's total area [27].

The nature and disc surface characteristics together with the abrasive properties, composition, and brake pad microstructure determine the frictional behavior of the braking system [28]. Most friction materials for vehicle braking systems are designed and developed considering that the contact surface is cast iron. The structural performance of the composite materials is presented in Table 2.

Fiber length influences the mechanical properties of composites with fibers. To obtain effective hardening and stiffening of the composite material requires a critical fiber length, which is 1 mm [29]. On the other hand, the fiber orientation in the composite material influences the hardness and mechanical properties [28].

The fiber alignment may be parallel to the long axes of the fibers in one direction, or they may have a disordered alignment. The alignment of the fibers leads to highly anisotropic properties in the composite, depending on the direction in which they are measured. Table 3 shows an illustration of the mechanical properties of the composite with metallic constituents for the brake pads (see Figures 2 and 4).

It is worth noting that the resistance on the sliding surface in the perpendicular direction is much higher than that in the parallel direction. This is due to the contribution to the mechanical strength of both the matrix and the fibers [28]. Thus, composite materials exhibit adequate mechanical properties and hence are suitable for use in braking systems. The characteristics of these materials are anisotropic due to the existence of the sliding surfaces of significant difference in the directions parallel and perpendicular (see Table 3).

The cracks are always initiated in the matrix in bending strength tests and propagate in the fiber direction before the fiber bundles are finally pulled out. The exposed fibers bear all the load after the failure of the matrix, leading to the subsequent destruction of the composite. Therefore, in bending tests, the material shows a pseudo-plastic behavior, without a sudden drop in load. However, between different types of composite products, there are significant differences caused by the manufacturing process and depending on the final composition and porosity.

Table 2. Structural performance of composite materials.

Property	Material			
	Metal	Ceramic		Polymer
		Volume	Fiber	
Tensile strength	G	P	V	G
Rigidity	VG	V	VG	P
Shock resistance	G	P	V	G
Elongation	G	P	VG	V
Hardness	G	G	G	P
Dimensional stability	G	V	G	P
Thermal stability	V	G	VG	P
Density	P	G	G	VG
Corrosion resistance	P	V	V	G
Erosion resistance	G	G	G	P
Hygroscopic	V	V	V	G

VG—very good; G—good; P—poor; V—variable.

Table 3. Mechanical properties of the composites with metallic constituents for the brake pads.

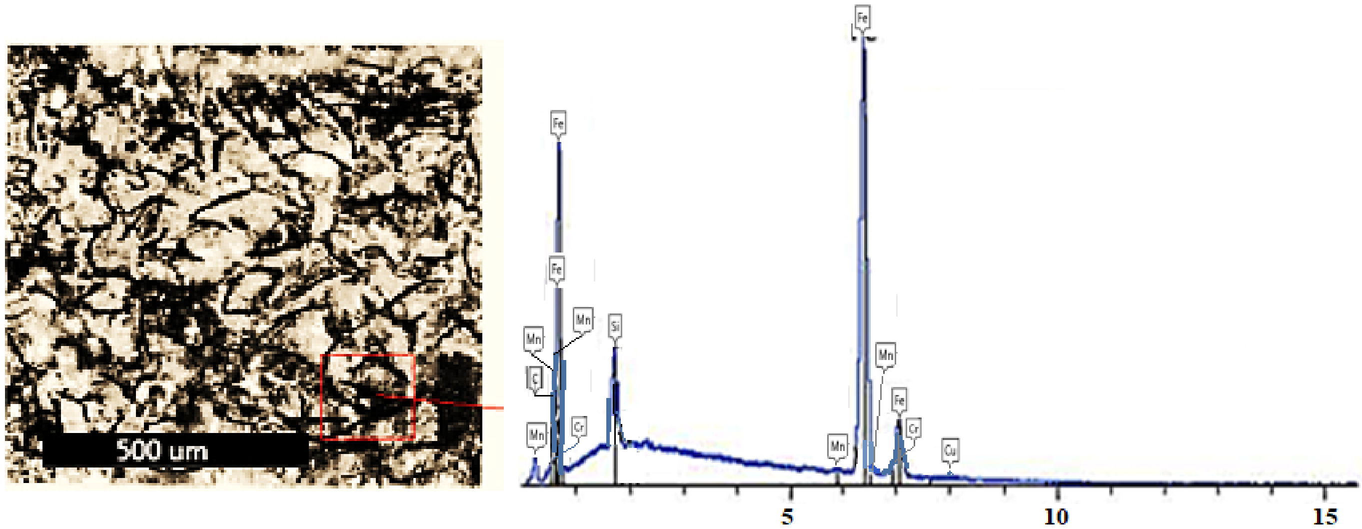
Flexural strength (MPa)	$\perp$	184 ± 25
	$=$	144 ± 34
Compression strength (MPa)	$\perp$	251 ± 48
	$=$	198 ± 39

$=$ parallelism.

Therefore, it was considered of great importance to also know the metallographic and chemical structure of the material of the discs and brake pads used in the braking system of vehicles. Thus, the metallographic and chemical structure together with the EDS spectrum were achieved on samples taken from the materials of a disc and a brake pad (see Figures 4 and 5) and are presented below.

The metallographic structure of the brake disc material sample (magnified by 500:1, from the selected area) is presented in Figure 6. According to the chemical composition, it presents a pearlitic gray cast iron with 3.34% C, 2.15% Si, 0.64% Mn, 0.03% P, 0.02% S, 0.04% Cr, 0.047%, and Cu, 0.041%, to which other chemical elements are added, such as Ni, Mo, Sn, V, Ti, W, and Sb, in very small amounts that cannot be detected, and the carbon equivalent (EC) $\approx$ 4.26.

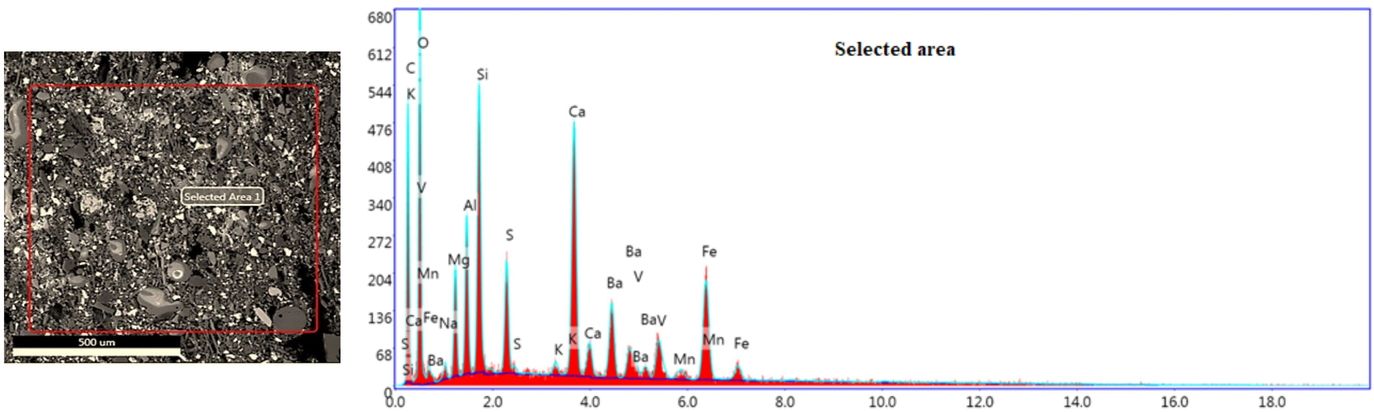
The metallographic structure of the brake disc material (Figure 6a) contains pearlite (dark islands), secondary ledeburite (dotted white field), secondary cementite (white areas), fine lamellar graphite (dark lamellar islands), and in the EDS spectrum (Figure 6b), can be seen the chemical elements that make up the chemical composition of the gray pearlitic cast iron. Overall, the structure of the pearlitic gray cast iron is normal, being free of structural defects.



(**a**) (**b**)

Figure 6. Metallographic structure of the brake disc material (**a**); EDS spectrum of the delimited area (**b**).

Of great importance is the metallographic and chemical structure of the brake pad material. Thus, the sample from the brake pad, according to the metallographic structure (magnified by 500:1, from the selected area) and the chemical composition is a metal composite with 10% C, 9% O, 1% Na, 5% Mg, 6% Al, 12% Si, 7% S, 2% K, 14% Ca, 6% Ba, 2% V, 5% Cr, 2% Mn, and 19% Fe, as shown in Figure 7.



(**a**) (**b**)

Figure 7. Brake pad material metallographic structure (**a**); EDS spectrum of the delimited area (**b**).

Therefore, the metallographic structure of the brake pad material (Figure 7a) contains a lot of metal materials in significant proportions (51% in total), but also carbon in a proportion of 10% (that is, a metallic composite), and in the EDS spectrum, the chemical elements that make up the chemical composition of the metallic composite can be observed (Figure 7b). Overall, the structure of the metal composite is normal and free of structural defects.

Regarding the tribological analysis (the behavior of the analyzed materials during the friction and wear process [30]), the role of the metal in the composite friction materials was studied, without being correlated with a mechanism. The study focused on a non-asbestos formula that was added to steel fibers (SF), brass (BF), and copper powder (CP). The total content was balanced with barite to keep the remaining components of the formula constant. The main effect of these metals (demonstrated by the tribological results) is to decrease the COF, due to increased speed or load, and Figure 8 shows the effect of speed on the COF.

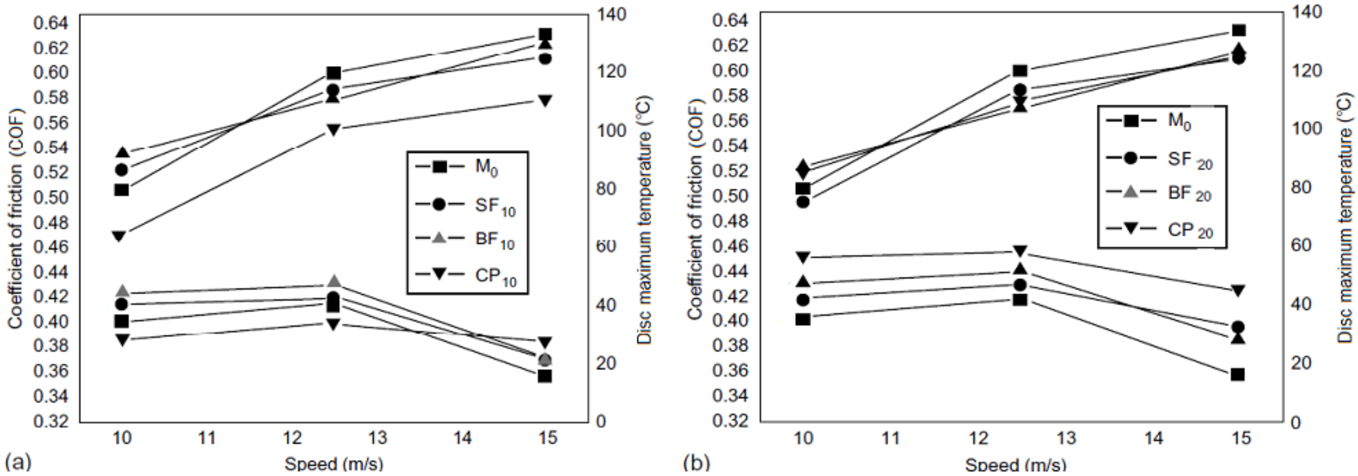


Figure 8. Effect of velocity on the COF of various metallic friction materials with 10 wt.% (**a**) and 20 wt.% (**b**): M_0—metal-free reference material; SF—steel fiber; BF—brass fiber; CP—copper powder. Index 10 si 20 represents the metal amount in weight (10 wt.% and 20 wt.%).

To determine the effect of velocity on various metal friction materials with mass/weight percentage (wt.%) of 10 wt.% and 20 wt.%, respectively, of their COFs, the pin-on-disc tribometer was used. Metal content of 10 wt.% was established and 20 wt.% to maintain constant asbestos-free and low-metal formula components and minimize the negative effects of metal on noise and vibrations, and thereby on stability, respectively, to maintain a constant coefficient of friction.

As seen in Figure 8, the COF has the smallest decrease with increase in speed for CP with 20 wt.% and the highest for M0 (the metal-free reference material). Therefore, the metals provide the stabilizing effect of the brake disc–pad pair and represent the real challenge of working with few metals. This challenge was made achievable by using materials that function as heat sink materials. Regarding the friction material wear, this is also strongly influenced by metals, but the general idea that they improve it can be true only to a certain extent.

In the case shown in Figure 9, the material with 10 wt.% metal (here copper (Cu)) had less wear than the reference material (metal-free, M_0) in both test conditions at load and speed. Instead, the material with 20 wt.% Cu had double the wear volume.

Compared to the SF, C and its alloys show increased wear due to the higher metal content. In this regard, it should be remembered that the SF substantially improves the strength of the material. However, excessive heat transfer to the brake pad weakens the bond near the material surface, as pure Cu is a metal with a high thermal conductivity (401 $Wm^{-1}K^{-1}$) and this leads to greater material wear.

The surfaces (Figure 10) of materials M0, CP_{10}, and CP_{20} under electron microscopy show significant morphological and topographical differences, which are correlated with the reduction in the COF and the rate of wear. However, since the wear debris is much smaller than in the other cases, where the wear rate is low, the plateaus are not very extensive.

In addition, it appears that the friction material microstructure covering the largest surface is almost intact, and hence the binder continues to work. The material surface M0 has a large composite oxide plateau and some detachments. Since the COF between oxide surfaces is usually lower than between metal surfaces, this extended oxide tribofilm is responsible for the decrease in COF with increasing speed or load.

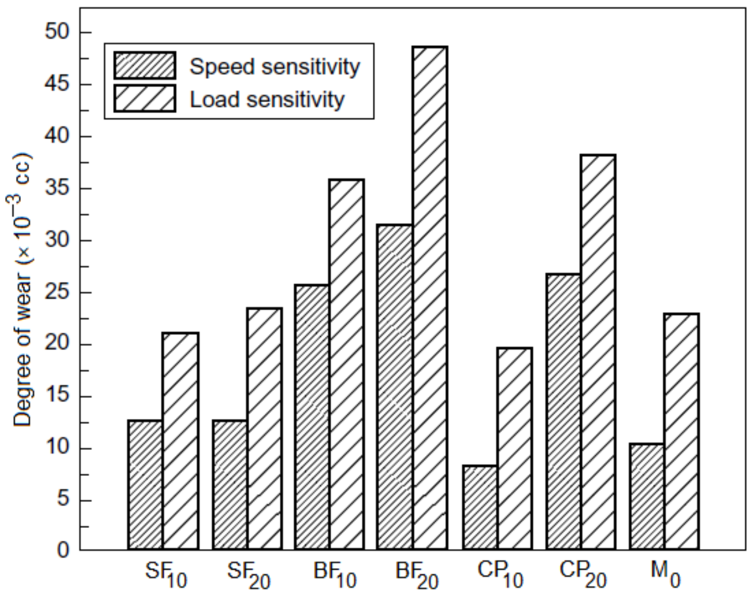


Figure 9. Cumulative wear behavior of composite materials based on two test methods, with speed sensitivity of 10.0, 12.5, and 15.0 m/s, respectively, load sensitivity of 2, 3, and 4 MPa, speed of 12.5 m/s, and load capacity of 3 MPa.

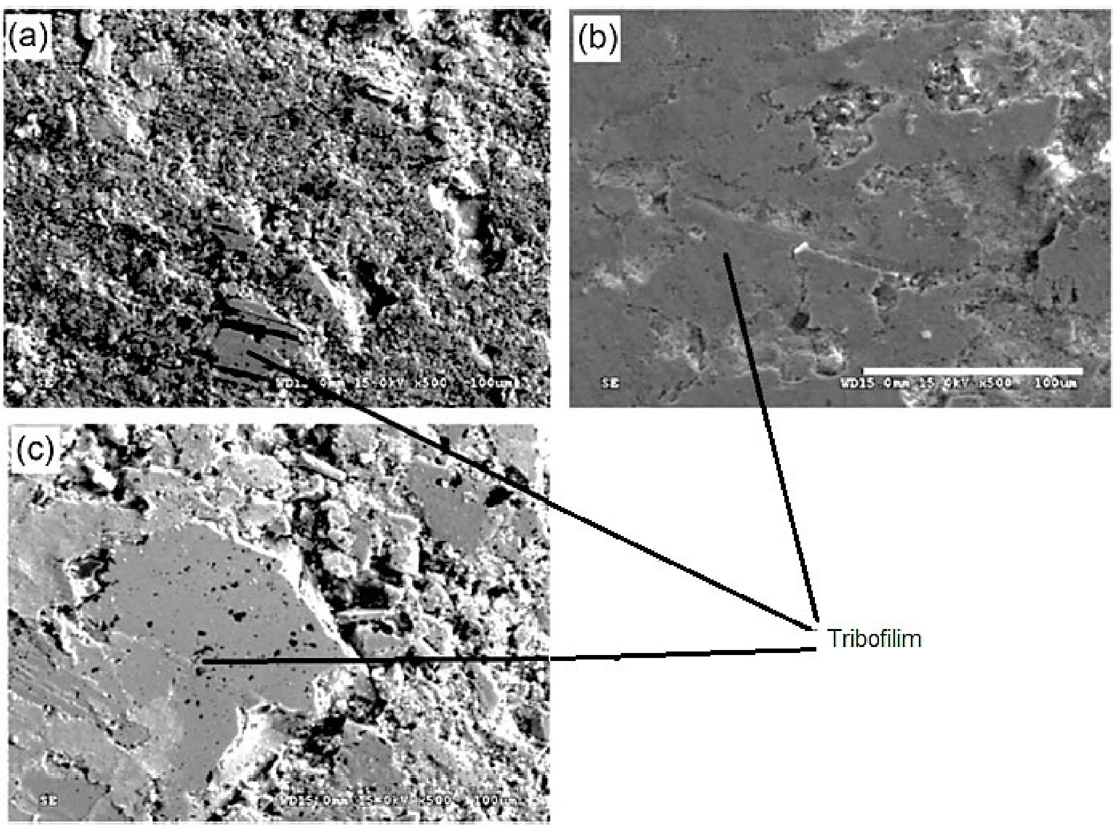


Figure 10. SEM images: (**a**) CP_{10} (low wear and discoloration), (**b**) M_0 (high discoloration), and (**c**) CP_{20} (high wear, low discoloration).

It is worth noting that the disc is also covered with an oxide tribofilm. A rough surface presents CP20 with a large plateau of secondary junctions (oxidized wear debris), and in the large areas where detachment occurs, raw material particles appear. This may indicate that binder failure due to excessive heat transfer towards the friction material caused much particle removal and the formation of oxidized wear debris and oxides that eventually formed the layer. However, the fresh metal particles emerging at the surface preserve/maintain a high friction coefficient.

Therefore, the friction materials with low steel (SF) are less subject to a strong sensitivity to speed and load than low metal ones. As a result, based on these characteristics, friction materials with little steel are more suitable for front axle uses. The true performance challenge is represented by the friction materials with low metal and the so-called ceramic materials.

4. Conclusions

Friction materials play an important role in vehicle braking systems, traffic conditions, and road safety. For this, it is necessary to understand the effects of structural property modification and tribological phenomena characteristics (friction and wear).

Technical specifications of commercially available frictional materials give the tribological and mechanical properties, indications regarding temperature effects, and operating recommendations. The COF of frictional materials depends on their microstructure and composition and can only be evaluated by testing friction material.

By metallographic and chemical analysis of the brake pads, determination of the tribological and mechanical properties, respectively, was solved with regard to some complex problems encountered in the braking system.

For a reliable chemical characterization, from the EDS analysis by elemental mapping, the existence of a large number of chemical elements in the pad and disc material composition of the brake was found. Because the nature of the material was not known, metallographic attack was used, to highlight the crystalline structure of this one. A normal structure without faults of the pad or disc material of the brake was observed.

For a complete analysis, some mechanical properties subjected to compression and bending stress were also measured, showing high resistance in a perpendicular direction in both cases. Also, the sliding resistance in the perpendicular direction was much stronger than in the parallel direction. This is desirable because it gives the brake discpad couple good tribological behavior (high friction coefficient, minimal wear), and hence an extension of life.

Tribological results showed that the main effect of metallic constituents on ceramic materials is decreased COF due to the increase in percentage weight of metal and increased speed or load. Instead, the ceramic material with the lower percentage weight (10 wt.%) of the metal had less wear than the metal-free one under both load and speed testing conditions, while the material with the greater percentage weight (20 wt.%) had double the wear volume.

Further studies are needed on braking systems to validate their microstructure and chemical composition, and the creation of new friction materials must be tested to generate a database and maps of the friction zones.

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Abbreviations

COF	friction coefficient
EDS	energy-dispersive X-ray spectroscopy
Wt	mass/weight percentage (%).

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