Studies and research on the tribological behavior of the braking systems of vehicles. Review

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Abstract. Given the current context and the advanced stage of technology, which the braking systems of vehicles have reached, the main purpose of the studies and research is focused on presenting the main tribological aspects that contribute at improving the performance of braking systems, in order to ensure the vehicles' safety and stability at braking, in any conditions. The performance of the braking system is a key factor for both producers and vehicle passengers, due to safety requirements, ever-increasing. Thus, over time, numerous studies and research have been carried on in order to improve the performance of the braking system. In this paper are studied tribological phenomena through those, which contribute to the improvement of the braking system as performance, safety and stability.

1 Introduction

Given the economic importance of the automotive industry, the impact it has on modern society, many studies have focused on improving the performance of vehicles [1].

Braking systems are essential for operating a vehicle in safe condition for both the driver, and for the other traffic participants. Therefore, the braking system is submitted to strict legal conditions. The efficiency and reliability required for braking systems over time have implied their continuous improvement [2].

Considering the fact that braking is a vital process, the elements of the system must be thoroughly designed, produced, maintained, and controlled. Research and development of new braking systems should be based on previous systems by testing their characteristics which, to a certain extent, have not met the needs, as well as the reliability of the system itself. The development of the system should be based on this experience, in order to not repeat the same disadvantages in the structure of the system, and to make efforts in order to obtain total quality and reliability [3].

Continuous improvement is needed to achieve a high-performance braking system that ensures a safe and stable braking at any speed. One such improvement to the braking system, is the addition of ferrite magnets to the disc brake system, so that the stopping

power of the vehicle increases. Thus, both the distance and the braking time decrease considerably, so that the braking is smooth and stable at high speeds [4].

The occurrence of squeaking and other phenomena in the braking system can be reduced by decreasing the coefficient of friction, but with its decrease, the performance of the braking system decreases [5]. A good comprehension and prognosis of the tendency of squeaking in car braking systems is an essential issue encountered by automotive engineers. As an example, a significant number of studies on finite element models (FEM) for car brake squeak have been carried on in the last two decades [6-13]. Many techniques are accessible in order to predict this behavior. Two main categories are distinguished: dynamic transient analysis and complex eigenvalue analysis (CEA) of car braking system. Researchers proposed complicated models with several degrees of freedom, because the model with movable caliper neglects the interaction between the disc and the plate. Shin [14-15] simplified the physical model into a system model with two degrees of freedom, coupled with a pair of disc pads and a disc; this study found the periodic and chaotic vibration of the system [3].

In order to avoid the squeaking as much as possible, various uncertain parameters were taken into account, namely the coefficient of friction and two insignificant wights, added to the brake caliper, which correlate to the structural changes of the braking system. Thus, it was possible to estimate the impact of structural changes on the stability of the braking system and to obtain information to select the best design of the braking system [4].

Thus, over time, numerous studies and research have been carried out in order to improve the performance of the braking system, such as: the design of the components and the whole assembly, of the braking system; materials used for contact surfaces; type of braking system: mechanical system, hydraulic system, pneumatic system, vacuum system, magnetic system, electrical system, regenerative electro-mechanical system.

Research and development of the new braking systems should be based on previous systems, to a certain extent, until when they will no longer meet the requirements, needs and reliability of the system itself, so as not to repeat the same disadvantages in the structure of the system and for making efforts, in order to obtain the total quality and reliability.

The reliability of the braking system, or any other technical system, is the ability to perform the required function without interruptions or defects. Nowadays, many auxiliary control and assistance systems have been incorporated into the braking system to help the driver in critical and challenging situations, as well as to provide it with more comfort in traffic conditions. Therefore, the paper highlights those tribological phenomena, through different parameters, which must be considered in choosing the braking couple that will be performing efficient, stable and safe.

2 Theoretical aspects

The disc brake incorporates a rotating disc with a circular plate. The disc is attached and rotated by the wheel hub. A caliper, which moves on the disc, is assembled on the suspension bracket, the hub shaft or shaft housing (Figure 1).
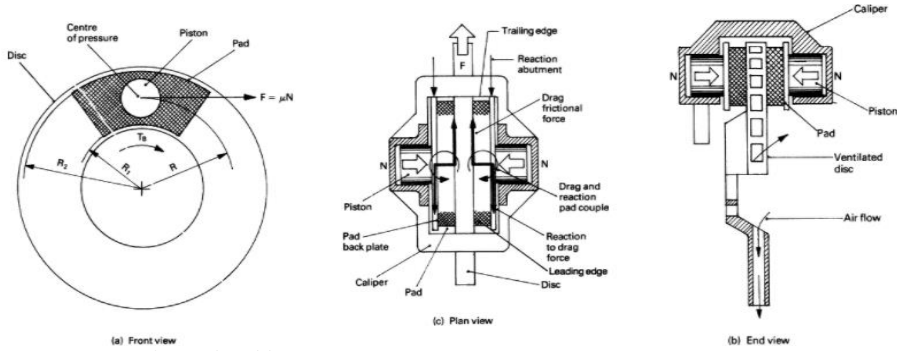
Fig. 1(a–c). Disc and pad layout [16]

In fig.1 the caliper is assembled with a pair of pistons and brake pads. When the brake pads are applied on the disc, they are locking it, causing the speed to be reduced, in accordance with the hydraulic pressure present in each piston. The hydraulic pressure is generated by the effort made by operating brake pedal [16].

Having regards to the fundamental principles of the braking system during movement, a vehicle has a kinetic energy, whose value depends on the mass and speed of the vehicle. The engine produces the necessary energy that accelerates the vehicle from starting to the desired speed, but this energy must be dissipated in part or in full, when the vehicle speed is slowed down or completely stopped. Tus, the function of the brake system is to convert the kinetic energy held by the vehicle at any given time, into thermal energy by friction (Figure 2) [17].
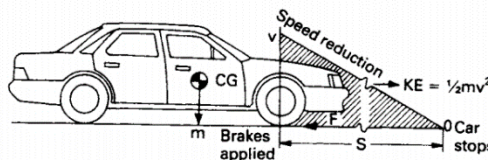
Fig. 2. Braking conditions of the vehicle [17]

The equation of kinetic energy, or the energy of motion, can be given by

$$E_c = \frac{mv^2}{2} \tag{1}$$

where:

E_c - vehicle kinetic energy (J); m - mass of the vehicle (Kg); V = vehicle travel speed (m/s).

The effort required to stop the vehicle is given by the relation:

$$E_w = F \times s \tag{2}$$

where: Ew - effort required to stop (J); F - average braking force (N); s - distance traveled (m) [16].

If a vehicle brakes until it stops completely, the effort exerted by the braking system must be equal to the initial kinetic energy of the vehicle, meaning:

$$E_w = E_c \tag{3}$$

$$F \times s = \frac{mV^2}{2} \tag{4}$$

So:
$$F = \frac{mV^2}{2s}$$
(5)

Braking distance and efficiency

Braking involves the process of generating a force that opposes the movement of the vehicle's wheels, thus minimizing the speed of the vehicle or stopping it. The force or resistance applied to stop a vehicle or reduce its speed is known as the braking force.

The braking efficiency of a vehicle is defined as the braking force produced as a percentage of the total weight of the vehicle, i.e. [17]:

$$Braking\ efficiency = \frac{Braking\ force}{Vehicle\ weight} \times 100\%$$
(6)

When the braking force is equal to the total weight of the vehicle that is being stopped, the braking efficiency is noted as 100%. Braking efficiency is usually less than 100% due to roads, the vehicle travels on a downhill slope or the braking system is inefficient.

The braking efficiency can be estimated by value the coefficient of friction, which is the ratio between the friction force and the normal load between the friction surfaces [17].

$$Friction\ coefficient = \frac{Friction\ force}{Normal\ load},$$
(7)

$$\mu = \frac{F_f}{N}$$
(8)

$$\mu = \frac{F_f}{N} = \eta\ \%$$
(9)

where: μ - coefficient of friction; η - braking efficiency (%); F_f - friction force; N - normal load.

Therefore, a 100% braking efficiency is equal to a coefficient of friction, so equal to 1:

$$\eta(100\%) = \frac{F}{N} = 1$$
(10)

Determination of braking distance

An approximate estimate of a vehicle's brake performance can be made by applying one of the equations of motion, assuming that the brakes have a 100% efficiency [17], namely.

$$V^2 = U^2 + 2gs$$
(11)

where: U - initial braking speed (m/s); V - final speed (m/s); g - deceleration caused by gravity ($\approx$ 10 m/s²); s - stopping distance (m)

If the final speed of the vehicle is zero ($V = 0$), then:
$$0 = U^2 + 2gs$$

$$s = \frac{U^2}{2g} = \frac{U^2}{2 \times 9.81} \approx \frac{U^2}{20}$$
(12)

It is necessary to transform from km/h to m/s:

$$U\left(\frac{m}{s}\right) = \frac{1000}{60 \times 60} U = 0.28\ U\left(\frac{km}{h}\right)$$
(13)

$$s = \frac{(0.28U)^2}{2g} = \frac{(0.28U)^2}{2 \times 9.81} = 0.004U^2 (m)$$
(14)

A table of vehicle breaking distances for distinct vehicle speeds and braking efficiency is presented in Table 1 [17].

Table 1. Braking distances for different vehicle speeds and braking efficiency [17]

Travel speed	Braking distance for different braking system efficiencies					
Km/h	100%	90%	80%	70%	60%	50%
10	0.4	0.4	0.5	0.6	0.7	0.8
20	1.6	1.8	2.0	2.3	2.7	3.2
30	3.6	4.0	4.5	5.1	6.0	7.2
40	6.4	7.1	8.0	9.1	10.7	12.8
50	10.0	11.1	12.5	14.3	16.7	20.0
60	14.4	16.0	18.0	80.6	24.0	28.8
70	19.6	21.8	24.5	28.0	32.7	39.2
80	25.6	28.4	32.0	36.6	42.7	51.2
90	32.4	36.0	40.5	46.3	54.0	64.8
100	40.0	44.4	50.0	57.1	66.7	80.0

3 Materials and methods

Friction materials play only a part in the friction. The vehicle's brakes consist of discs or drums, usually fabricated with cast iron as contact surface. Moreover, the category of cast iron (graphite flakes, spheroidal graphite, etc.), but also the precise metallurgical components, hold a highly important role. Some elements, such as vanadium, even in small amounts, have a great impact over the friction and wear performance of certain types of materials, while other elements, such as titanium, in large amounts, will affect friction and wear performance, but it can also make it indeterminate [18-19].

The evolution of friction materials is presented in Figure 3. All the main issues that were encountered in the past 20 years are described with their solutions. Many studies and researches lead to materials that are used today, with different metals and sulfides, although the current issue represents reducing the percentage of heavy metals used in friction materials.
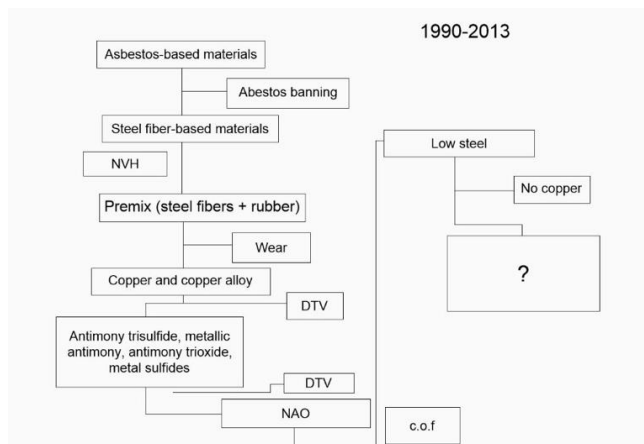
Fig. 3. Evolution of friction material formulas in the past two decades
NVH = noise, vibrations, hardness; DTV= Disc thickness variation;
NAO= Non asbestos organic materials; c.o.f= coefficient of friction [20]

Table 2 shows that the selection of the friction material is of paramount importance. For cars and trucks, disc brakes are mainly designed with cast iron as friction material, while for motorcycles disc brakes are made of stainless steel. The wet performance of stainless steel is significantly lower than the dry performance, in some case even 3 times lower. [22].

Table 2. Friction coefficients measured for different materials
in the disc - brake pads assembly [20]

Material	Coefficient of friction measured on diameter of 1 cm and specimen material at equilibrium, with slip speed 1 m/s, interface pressure 0.689 N/m^2, Initial temperature 80 °C
Graphite cast iron flakes	0.40
Mild steel	Very irregular frictional forces measured
Stainless steel	0.60

Organic friction materials
*a) Semi metallic materials*

The so-called semi-metallic formulas are defined by a high metal percentage, usually exceeding 50% of the total mass. Metals components are abundant in steel fibers, copper, copper alloys (bronze and brass), tin and zinc in some cases. Other components are represented by a mixture of strong abrasives and lubricants. In Table 3, the components of non-asbestos friction materials are presented [20].

Table 3. Percentage of lubricants and metals in NAO materials, low steel, low metal [21]

| Raw materials	Ceramic materials (%)	Materials with low percentage of steel (%)	Materials with low percentage of metal (%)	Semi-metallic Materials
Lubricant				
Fine graphite	4-9	2-8	4-10	4-10
Coarse graphite	2-5	0-7	4-8	5-10
Fine graphite				
Fine graphite	2-5	2-5	2-5	2-7
Cu sulfide	2-5	2-5	2-5	2-10
Other sulfides	0-4	0-4	0-4	2-5
Ferrous metals				
Iron fibers	0	10-18	5-10	20-35
Steel powder	0	2-5	1-2	2-7
Non-ferrous metals				
Copper	10-16	6-15	0-6	2-10
Copper alloys	5-10	5-10	0-5	2-10
Zinc / Sn	0-4	0-4	0-2	0-4

Figure 3 shows some classic proportions between the main component classification: abrasives, lubricants, total metals, including steel fibers, non-ferrous metals, graphite and sulphides for ceramic formulations, alloy steel and semi-metallic formulas. Abrasives in semi-metallic formulas are typically strong abrasives (alumina, and rarely corundum) that have the role of removing oxides from the contact surface of the disc. Ceramic materials require only weak abrasives (silicate of zircon).
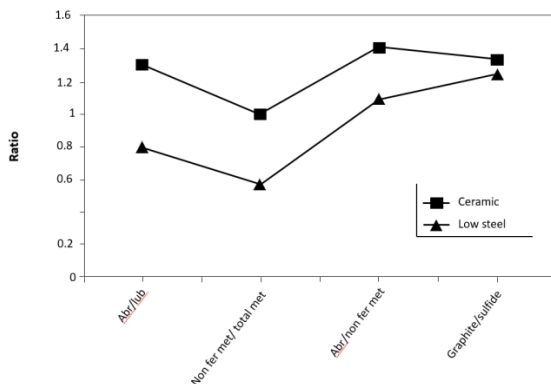
Fig. 3. Typical ratios between the main categories of materials [21]

b) Materials with a small amount of metals

Low metal materials are defined by a low percentage of metals in their formulas. Since squeaking and noise are caused by a higher quantity of metals, the main role of this type of material, is to increase the comfort. Still, this type of materials, are sully used for the rear axle, as their performance and coefficient of friction (0.35-0.38) is lower than the coefficient of friction of semi-metallic materials, which is 0.4. An application with a copper composite that replaces the classic cast iron for the brake disc is shown in Figure 4. [21]
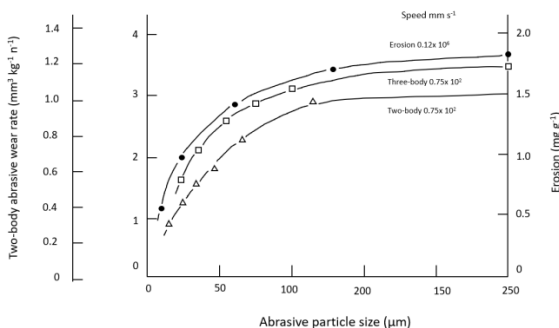

Fig. 4. Rate of wear of copper under conditions of abrasion (with two-body, three-body and the erosion) caused by silicon carbide particles of different sizes [21]

c) Materials with a small amount of steel

Formulas with a small amount of steel, are similar to formulas with a low metal content. The higher content of steel fibers provides a very high coefficient of friction, which makes these materials appropriate for the front axle. As fewer abrasives are required for this type of materials, the negative effects of noise and vibrations can be minimized. This damping system stands in need of the use of rubber and lubricant premix, as in the case of semi-metallic formulas. In order to stabilize the coefficient of friction, MgO is used as a gentle abrasive. The proper balance between the oxide tribofilm and the growth can achieve the stabilization of the coefficient of friction, as there is essential to maintain a constant coefficient of friction, when there is only one source of iron. [21]. An important study conducted by Kumar and Bijwe [21] describes, the importance of metals in friction materials. The study is concentrated on steel fibers, brass fibers and copper powders introduced in an asbestos-free formula, equilibrating with barite, the whole formula, and preserving continuously the other elements of the formula. The metal percentage was studied in two cases, 10% and 20%. The results highlighted that the main impact of these

metals, represents a decrease in the coefficient of friction cause by either the increase in speed or the load. Figure 5 shows the impact of speed over the coefficient of friction [21].

(a)   (b)
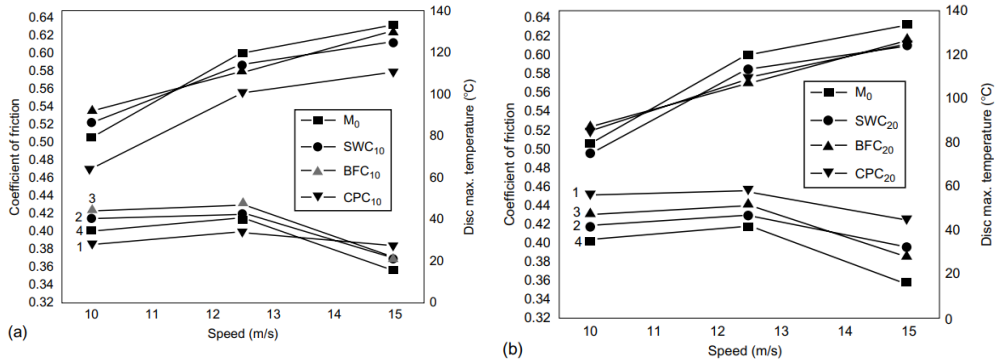
Fig. 5. The effect of speed on different friction materials with metals, with a percentage mass of 20% , determined with the disc tribometer. M_0 - reference material without metals; SWC- steel wool; BFC - brass fiber; CPC - copper powder (sub-index 20 indicates an amount of metal is 20%) [21]

d) Ceramic materials

These materials are in need of copper to promote heat dissipation, as they do not have steel fibers in their formulas. Steel is commonly used in other types of material and has a great impact in thermal conductivity. Metals, in addition to their influence on the coefficient of friction, have an essential role in heat transfer between the brake pads and friction surface. Materials with a low quantity of metals, are an important replacement to this laborious issue. [21]. Thus, as it is specific in friction materials, in order obtain a proper properties balance, combining ceramic materials, which have a low thermal conductivity (zirconium), with others that have a good thermal conductivity (magnesium oxide and silicon carbide), is essential (Figure 6) [21-22].
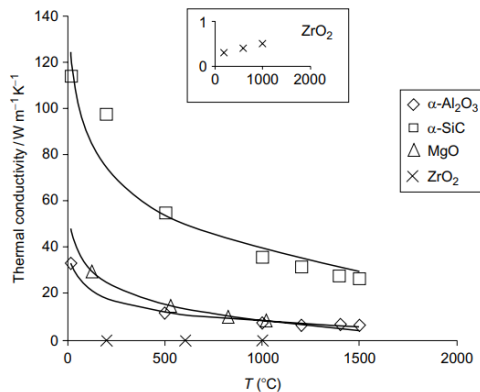

Fig. 6. Thermal conductivity of ceramic materials [21]

e) Carbon-ceramic discs and friction materials

In the last 10 years, a new type of material has been designed: carbon-ceramic materials, especially carbon / carbon-SiC (C/C - SiC) (figure 6). This type of material has a low density, such as 2 gcm^{-3}. Carbon-ceramic discs are currently used for the high-end cars, as they are a lot more expensive than other materials, but still more affordable than carbon-carbon materials [21]. Figure 7 presents the aspect of carbon / carbon-SiC during different stages of fabrication.
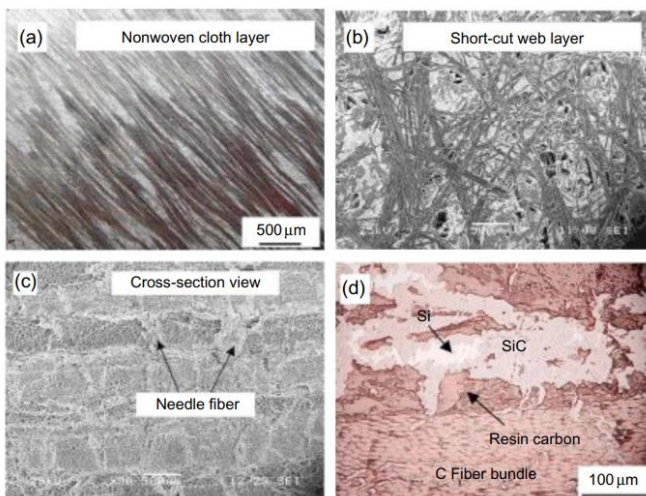
Fig. 7. Microstructure of composite C / C - SiC: (a) Nonwoven layer, (b) Cut fabric layer, (c) needle fibers and (d) the various components of the final material [21].

In the compression test, for the perpendicular direction, both the matrix and the fibers support the load, and the cracks cross both frames. The behavior is elastic until the material suddenly breaks. In Table 4, mechanical properties of a C / C - SiC composite are presented. It must be noted that the strength in the parallel direction is significantly lower that the strength in perpendicular direction, due to the contribution to the mechanical strength of the matrices and fibers. [21-22].

**Table 4.** Mechanical properties of C / C - SiC composites [21]

Bending strength	⊥	174±22 kN/m
	∥	134±31 kN/m
Compression strength	⊥	241±45 kN/m
	∥	188±36 kN/m

4 Results and discussions

In Figure 8, the wear in different conditions, such as load and speed tests, is discussed. The results show that materials with 20% wt of copper present a significant wear in comparation with the reference material, while the material with 10% wt copper has the least wear. This concludes that the wear is caused by copper and its alloys, while steel fiber impacts positively the strength of the formula. Copper also has a good thermal conductivity ($401 Wm-1K-1$), which implies and excessive heat transfer to the brake pads, resulting in the destruction of the binder near the friction material, causing an increase in wear. [21-22].
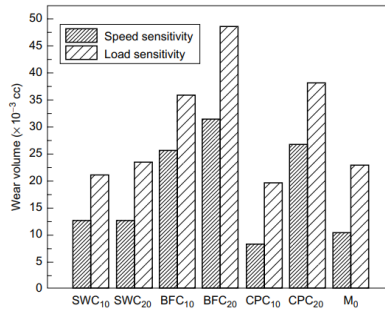
Fig. 8. Cumulative wear behavior of the selected composites in two test modes [21]
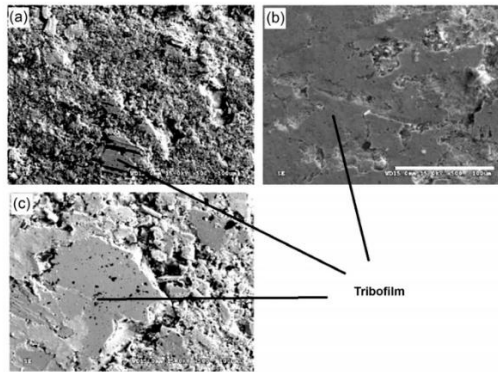
Fig. 9. SEM images: (a) CPC_{10} (low wear), (b) M_0 (reference) and (c) CPC_{20} (high wear) [21]

In principle, Amontons' friction laws apply to friction materials. Still, for resin/cast iron composites, the friction toque and coefficient of friction do not remain constant, due to the variation of the temperature. When the bakes are applied, the temperature at the friction interface increases, resulting in a high temperature of the friction material, even in low operating condition, due to low thermal diffusivity of the friction material. As a result, the friction material is thermally destroyed. Thus, the coefficient of friction, μ, changes with temperature; typically, μ increases slightly until the temperature of the disc or drum is approximately 200-250 °C and then decreases as shown in Figure 9. The exact temperature variation depends on the characteristics of the friction material (Table 5) [20].
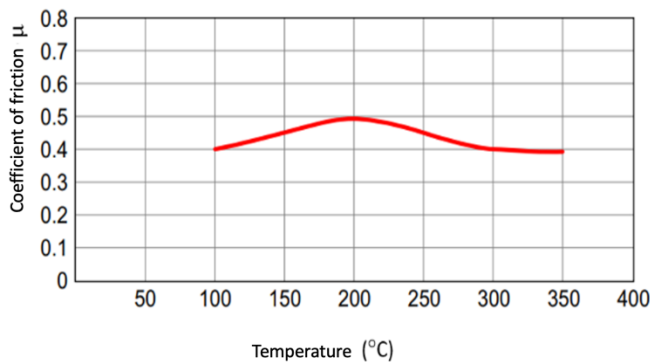
Fig. 10. Variation of the friction coefficient with temperature for resin-bonded composite material [20]

Table 5. Example of specifications of the characteristics of friction materials [20]

Example of specifications of the characteristics of friction materials	
Maximum tensile strength	15 MPa/m^2
Maximum tensile strength	25 MPa/m^2
Rockwell hardness	25 MPa/m^2
Density	1950 kg/m^3
Recommended maximum working temperatures	
Ongoing	250°C
Flashing	350°C

For extended operation at temperature above 300 °, resin-bonded materials associated with conventional cast iron disc, will develop changes in the friction material and probably in the thickness of the plate or friction material. The organic elements that have the role of controlling wear and friction properties, begin to deteriorate thermally. Therefore, the mechanical strength of the material is decreasing, and the friction material is severely impacted. As a result, the surface of the friction material will be "denatured", because all organic elements are burned and only the temperature-resistant elements remain unaffected. Friction and wear resistance are irreversibly damaged [20].

5 Conclusions

Friction materials represent a vital part of car and vehicle brakes. Design engineers must recognize the behavior of wear and friction and the origins of the discrepancy in their properties [15].

Requirements for commercially friction materials are represented by mechanical, friction, and wear properties. These properties indicate recommendation for operating condition and the impact of the temperature over the friction material. Their coefficient of friction is in a strong dependence with their composition, thus automakers will choose friction materials that meet their requirements; for example, for niche cars, friction materials that have a nominal value of the coefficient of friction between $0.38 < \mu < 0.45$, while trucks require durability, thus friction material for trucks require a coefficient friction between $0.35 < \mu < 0.40$. These values represent the starting point for designing the braking system [20].

A friction torque practically follows the friction laws of Amontons, but when the braking load increases and the temperatures generated at the friction interface increase significantly, the coefficient of friction will vary. Often, variations in the coefficient of friction are in accordance with the temperature. These changes are in close dependence with the properties of the friction material. The coefficient of friction of any friction material can only be accurately determined by testing.

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