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STRUCTURAL AND TRIBOLOGICAL ANALYSIS OF BRAKING SYSTEM MATERIALS DISC WITH BRAKE PADS

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Abstract: The study of the tribological behavior of the braking system in auto vehicles requires knowing the characteristics of the materials in contact with the friction pair, brake disc–pads, in the work process. Analysis of the materials is necessary because the wear process depends on the friction pair, and brake disk–pads, respectively on the parameters of the work process (rotational speed, pressing force, traffic conditions, etc.). The material of the brake discs is generally the same gray cast iron, but the brake pads can be semi–metallic (combination of metallic and non–metallic materials, all bonded with a special resin), organic materials (non–metallic components such as glass, rubber, and kevlar all joined with the help of a resin) and ceramic (they have only ceramic material as a composition, rarely have small copper particles). The purpose of the work is to know the crystalline structure and the mechanical properties of the brake pad materials, through specific analyses, with important implications on the friction and wear behavior.
Keywords: disc and brake pads, metallographic structure, tribological properties, braking system

1. INTRODUCTION

Evolution in time of the braking systems has meant continuous improvement to be efficient and reliable [1]. A vehicle's braking system is considered an energy–dissipating device, converting momentum (kinetic energy) into heat (thermal energy). Speed control is the brake's primary function, and the rate of deceleration of the vehicle is defined by energy dissipation.

Main objective of the braking system study is to improve its performance to ensure a safe, stable braking, in any conditions/situations. Such an improvement, brought to the braking system, is also represented by the structural changes in the materials of the disc–brake pads pair. The creak, noise, and vibrations are the braking system problems. These problems can be solved by decreasing the friction coefficient (COF) but with it is decreases also the performance of the braking system [2]. Thus, these aspects 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 been made considering different uncertain parameters, such as the coefficient of friction and other constructive parameters to the caliper. To avoid as much as possible the creak, noise, and vibrations occurrence, these parameters assume classic structural modifications in the brakes design phase. In this way, it was possible information obtaining necessary for the choice of the best design of the braking system and to evaluate its stability due to the influence of structural changes [3].

Based on previous experiences it is necessary to develop new braking systems, and by testing their characteristics not to repeat the same disadvantages in their structure, but to obtaining the total quality and reliability [4].

Many numerical simulations were performed at the contact interface (friction) interface 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]. Therefore, the braking system performance represents one aspect of improving the friction materials properties, in particular, those of the contact surfaces. Thus, the brake creak phenomenon in frequency and amplitude terms of the limited cycle oscillations was analyzed by Ganji and Ganji in Ref. [6], considering the motion nonlinear equations due to large deformations [7]. Phatak and Kulkarni [8] achieved squeal reduction by structural modification and by studying the parameters affecting drum brake noise.

Also, they considered the study and revision of different material selection schemes, in order to find an optimized selection procedure [7]. The researchers proposed complicated multi–degree–of–freedom models. For example, Shin et al. [9, 10] to a braking system with periodic and chaotic vibration replaced the physical model with a model with two–degree–of–freedom.

Paliwal et al. [11] studied the coupling stiffness influence on the stability and anti–skid vibrations of the braking system, at the brake disc–pads interface. Yang et al. 12] used and studied flexible connection caliper–brake pads on a model with three degrees of freedom. Shen [13] made the brake pads with the three–layer, two layers of plastic (first and third), and the middle layer from felt. Such pads reduce noise,

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improve the impact resistance of the brake pads and ensure the braking system stability. Gao and Song [14] proposed the friction material for brake pads, to be obtained by the process of metal–based sintering because it improves the adhesion, COF, and wear resistance. Therefore, the single–layer brake pads, widely used in auto vehicles were replaced with the multi–layer ones (different materials). This transformation supposes the obtaining of brake pads with varying stiffness and damping by structural changes.

This process can reduce vibration and noise when braking; respectively the braking system stability can improve, but the braking system dynamics remains unclear. Also, Wei, et al. al. [15] proposed the two–layer pads (base layer and friction layer) by simplifying the three–layer one. The base layer acts as a support, while the friction layer is the one that contact the brake disc to produce the braking force. By optimizing the brake pad parameters, the appearance of chaotic vibrations was reduced [16], hence the braking system stability was improved. One of the aspects to be studied in the present paper with the purpose of the braking system improving is represented by the materials analysis used, especially those for the contact surfaces.

2. MATERIALS AND METHODS

The main purpose of braking systems is to achieve the required braking torque, which causes the wheel to slow down and therefore brake. Therefore, the braking torque is the main characteristic of these systems.

Modern vehicles are equipped with two types of braking systems, namely disc brakes and drum brakes (Figure 1) depending on the heat transfer conditions in the brakes [16], especially, but also the working conditions.

a) b)

Figure 1. Braking system: a) disc with pads; b) with shoes [17]

Today, most cars are equipped with brakes, disc–brake pads (Figure 1a) both on the front axle and also on the rear axle, while a percentage of cars, which continues to decrease, still use drum brakes on the rear axle.

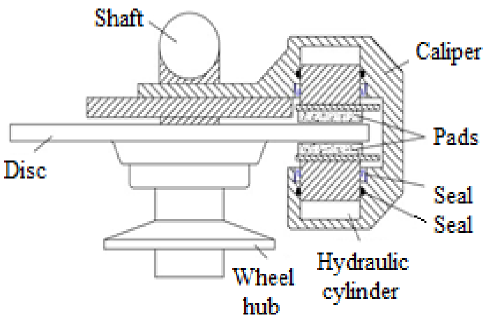

Figure 2. Assembly, disc with brake pads [19]

The braking system is basically a rotating cast iron disc rotated by the wheel hub and a bridge element, called caliper, which is fixed on the axle housing, hub axle, or suspension bracket depending on the constructive version, and it rides on disc (Figure 2). The caliper contains a of pistons and the brake pads pair, which by pressing the brake pedal lock the rotating disc, depending on the generated hydraulic pressure behind each piston and determines the speed reduction [18].

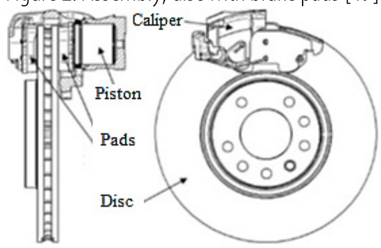

Figure 3. Brake assembly, ventilated disc with pads, and single–piston movable caliper [20]

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. Figure 3 shows a typical example of a braking system assembly; the slip between the disc and the brake pads is about half the vehicle speed. At the same time, the brake pads usually cover 10 – 15 % of the track surface which is described on the brake disc [20].

Normally, the discs of vehicles are made of gray cast iron, and the brake pads of composite materials contain different constituents (sometimes 10 or more), that are compacted into a solid mass with a porosity of 5 – 10 %, by hot pressing. Although these friction materials have a wide range of compositions and can be broadly classified, according to Table 1.

Table 1. Component elements of brake pads [20]

Description	Function	Example
Binder	Forms a thermally stable matrix	Thermosetting phenolic resin
Fibres	Provides mechanical properties	Brass, steel, kevlar, glass, ceramic
Lubricant	Stabilizes friction, especially at high temperatures	Graphite, metal sulphides
Abrasive	Cleans disc surface film and improves friction	Alumina, zirconium, metal silicates, chromium oxide,
Filler	Improves production and reduces costs	Barium sulphate, mica, vermiculite

Therefore, the methodology involves a structural, tribological, metallographic, and chemical analysis on samples taken from a brake pad used at a vehicle (car) and presented in the following.

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3. RESULTS AND DISCUSSIONS

The nominal pressure, during braking, varies usually from 1 to 10 MPa between the disc and the brake pad. However, the real contact area represents typically between 15 and 20% of the pad's total area and is distributed into a series of small islands (contact stains), which come out with a few microns above the pad surface, for moderate braking loads, and it is shown in Figure 4.

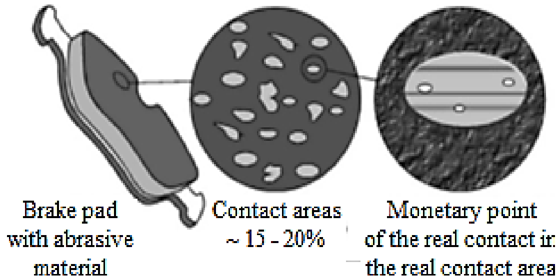

Figure 4. Visualization of the contact stains (contact area) on the pad surface following of friction with the brake disc [20]

The islands are usually from 50 to 500 µm in size and are hard prominent particles surrounded by soft material and wear debris. Each island forms and disappear quickly and has isolated contact points. The nature and disc surface characteristics together with the abrasive properties, composition, and microstructure of brake pads determine the frictional behavior of the braking system, disc–brake pads. Both vary with contact history, and the complex response demonstrates that a systemic approach is necessary to analyze tribological aspects. It is mentioned that most friction materials for vehicle braking systems were designed and developed, considering that the contact surface is made of cast iron.

The type of cast iron (with graphite flakes or spheres etc.), together with the metallographic composition, are very important because small or larger amounts of other elements (titanium or vanadium) strongly influence the performance at friction and wear or make it unusable. [21]. Stainless steel, for cosmetic reasons, is used for disc brakes and pads from motorcycles, and from Table 2, the importance of the selection of friction materials can be seen.

Table 2. Measured values of COF for the materials of the brake disc–pads pair [22, 23]

Material	COF was measured for a material specimen in equilibrium conditions at the initial temperature of 80°C, sliding speed of 1 m/s, and interface pressure of 0.7 MPa on a friction diameter of 10 mm.
Cast iron with graphite flakes	0.40
Soft steel	Friction forces measured and irregular, very high
Stainless steel	0.60

Semi–metals with a high metallic content of over 50% of the total mass are the most used materials for brake pads. According to Table 3, the components (metals, abrasives, and lubricants) of these semi–metallic friction materials without asbestos are presented.

Table 3. Percentage of components in non–asbestos semi–metallic materials [22, 23]

Raw materials	Ceramic materials, %	Materials with a small percentage of steel, %	Materials with a small percentage of metal, %	Semi–metallic materials, %
Lubricants				
Fine graphite	4–9	2–8	4–10	4–10
Coarse graphite	2–5	0–7	4–8	5–10
Sulphides				
Sulphide of Sn/Sb	2–5	2–5	2–5	2–7
Cu sulphide	2–5	2–5	2–5	2–10
Other sulphides	0–4	0–4	0–4	2–5
Other sulphides				
Ferrous metals	0	10–18	5–10	20–35
Iron fibers	0	2–5	1–2	2–7
Non–ferrous metals				
Cu	10–16	6–15	0–6	2–10
Cu alloys	5–10	5–10	0–5	2–10
Zn/Sn	0–4	0–4	0–2	0–4

The typical ratios between the main categories of friction material components: abrasives (A)/lubricants (L), non–ferrous metals (N–FM)/metallic materials (MM), abrasives (A)/non–ferrous metals (N–FM), graphite (G)/sulfides (S), respectively the ceramic formulas, semi–metallic formulas and with little steel, are shown in Figure 5. Ceramic formulas need mild abrasives (zircon silicate), while semi–metallic ones of strong abrasives (alumina and sometimes corundum) to quickly remove oxides from the disc surface.

The metal's presence is related to slippage and noise, hence the idea is to create formulas to ensure comfort. However, low metal percentage formulas can be suitable for rear brakes, because the average COF is 0.35–0.38, lower than 0.4 of the semi–metallic formulas. Tribological results have shown that the metal effect is to decrease the COF due to either increasing speed or load.

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The effect of the speed on the COF and the heating temperature is shown in Figure 6, for two versions of percentage weight (wt. %): with 10 wt. % by Cu (Figure 6 a) and 20 wt. % by Cu (Figure 6 b) [22]. It is noticed that the COF remains relatively constant up to a speed of 12.5 m/s, after which it decreases relatively much at speeds higher than 12.5 m/s, for all the materials analyzed, and the temperature of the brake disc, due to friction, increases relatively continuously, along with the increase in speed.

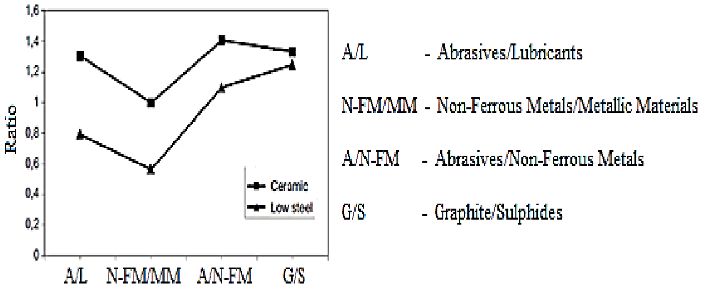

Figure 5. Ratio of the main categories of friction material components: A/L, N–FM/MM, A/N–FM, G/S, ceramic and a low amount of steel [22]

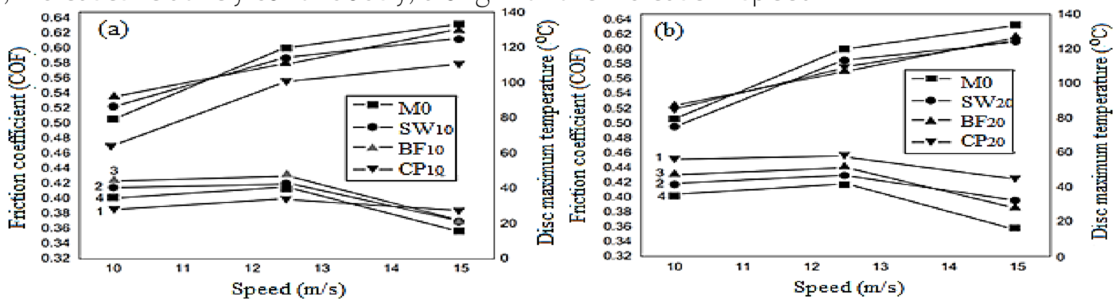

Figure 6. Effect of speed on the COF and the heating temperature of different metallic friction materials with 10 wt. % (a) and 20 wt. % (b): M0 – metal–free reference material; SW – steel wool; BF – brass fiber; CP – copper powder [22]

Referring to the wear behavior, for the cases shown in Figure 7, the material with 10 wt. % by Cu has less wear than M0, in both situations (depending on speed and load), while the material with 20 wt. % by Cu it doubles its wear volume. It is observed that Cu and its alloys increase the wear, more than steel fibers due to the higher metal content (Cu). Instead, the steel fiber contributes significantly to the strength of the material [22].

Comparing the surfaces by the scanning SEM (Figure 8) of three materials, M0 (Figure 8 a), CP10 (Figure 8 b), and CP20, Figure 8 c), shows significant topographical and morphological differences, in relation to COF mitigation and of wear rate [24]. Flat areas are not very extensive because the wear rate is low (i.e., the wear debris are few) compared to the other cases. In addition, appears relatively intact, and the friction material microstructure (i.e., the binder still working) because covering the largest surface. Instead, the surface of M0 (see Figure 8 a) shows composite oxides (tribofilm) on an extended area and some detachments have appeared.

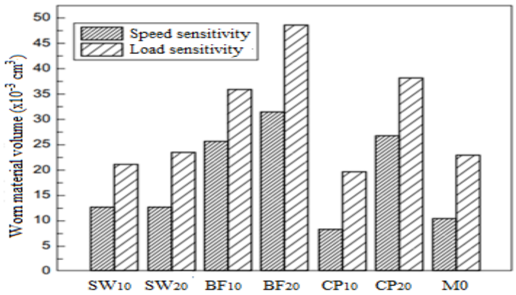

Figure 7. Speed effect of on the COF of various metallic friction materials with 10 wt. % and 20 wt. % of Cu [22]

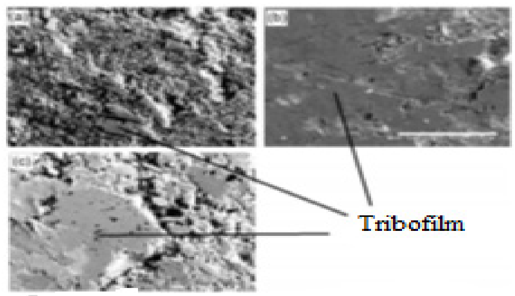

Figure 8. SEM images: (a) CP10 (low wear), (b) M0 (metal–free reference material) and (c) CP20 (high wear) [22]

This tribofilm is the cause of COF decrease with increasing speed or load since it generally is lower between oxide surfaces than between metal ones [22].

Because ceramic materials do not contain steel fibers should contain Cu to lead to heat dissipation and also it contributes to the overall thermal conductivity, being a common component and of the other friction materials. Metals, apart that influencing the COF, it contributes significantly also the heat transfer from the brake disc–pads interface, so to achieve a balance. An alternative to this difficult situation is low–metal (even steel) metallic materials.

A common ceramic formulation consists of binders 14 wt. %, fibers 4 wt. %, shock absorbers, and organic compounds 5 wt. %, abrasives 19 wt. %, lubricants 10 wt. %, sulfides 9 wt. %, non–ferrous metals 10 wt. % and filler material 29 wt. %.

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Thus, was developed friction materials new as the ceramic – carbon (C) materials, especially C/C – SiC, currently used for the brake discs of top cars, much more affordable than C/C materials, but more expensive than common (of cast iron). [22].

The C/C – SiC composer microstructure (Figure 9) is composed of a layer of non–woven material (Figure 9 a), a layer of cut fabric (Figure 9 b), acicular fibers (Figure 9 c), and the final structure contains all the components of the composite material (C fiber, C resin, Si and SiC, Figure 9 d).

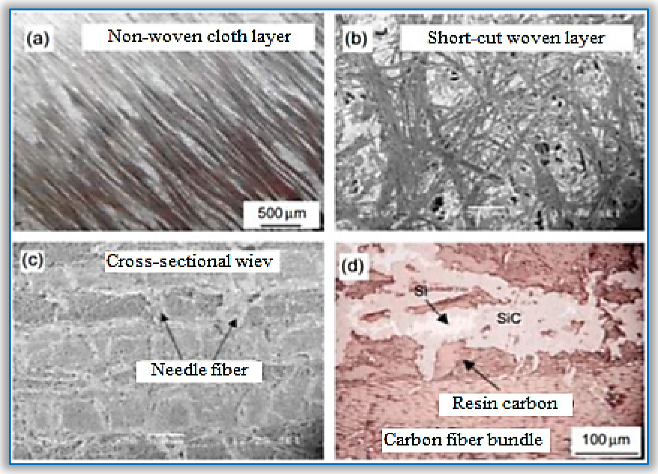


Figure 9. C/C – SiC composer microstructure: (a) nonwoven material layer, (b) cut fabric layer, (c) acicular fibers, (d) final material components [22]

Both matrix and fibers participate in mechanical strength (bearing the load) [22, 23], and both frames (matrix and fibers) are crossed by cracks in the perpendicular direction [20, 25] in compression tests. The material behaves elastically in this case until suddenly breaks (being tenacious).

An illustration of the C/C – SiC composite mechanical properties is presented in Table 4. It is remarked that the mechanical resistance is much higher in the perpendicular direction than that in the parallel direction, at the sliding surface.

Table 4. C/C – SiC composites mechanical properties [22, 23]

Resistance to bending, MPa	$\perp$	174±22
	$\parallel$	134±31
Resistance to compression, MPa	$\perp$	241±45
	$\parallel$	188±36

At braking systems, C/C–SiC composites are used, due to suitable mechanical properties. Because there are significant differences between the two directions ($\parallel$ and $\perp$ to the sliding surface), the mechanical properties of this composite are anisotropic.

There are also considerable differences between the C/C–SiC product variants depending on the manufacturing process, porosity, and final composition.

The cracks appear initially in matrice at the bending tests, which in time propagates along the direction of the fibers before most of the fibers (which bear the whole load) are finally exposed/broken, and after the deterioration of the matrix lead to the subsequent destruction of the composite. Thus, the composite material in bending tests behaves as pseudo–plastic, without a sudden drop–reduction in the load.

A metallographic and chemical structure of the brake pads material typically used in a tested vehicle was considered important. For this, samples were taken from the material of a brake pad.

The sample from the brake pad, according to the metallographic structure (magnified by 500:1) and the chemical composition (selected area), is a metallic 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; 19% Fe and can be observed in Figure 10.

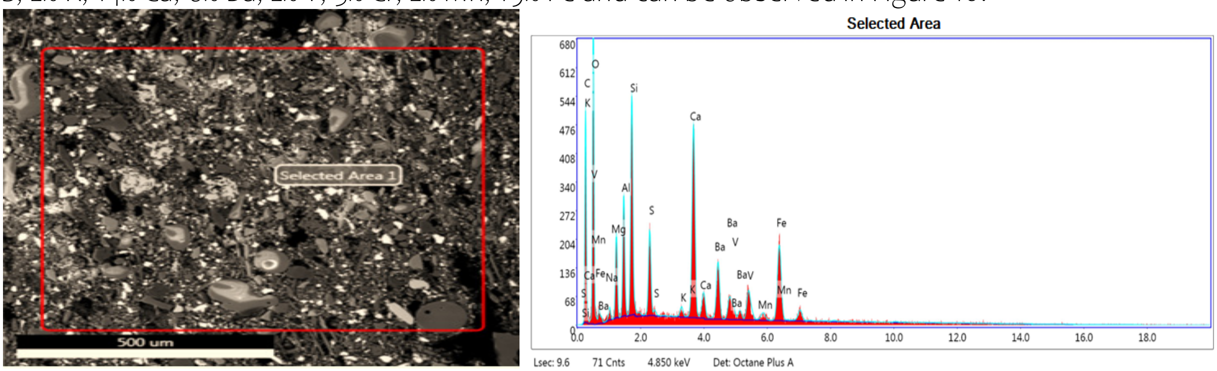
(a)  (b)

Figure 10. Brake pad material metallographic structure (a); EDS spectrum of the delimited area (b)

Therefore, the metallographic structure of the brake pad material (Figure 10 a) contains a lot of metal materials in significant proportions (51% in total), but also carbon in a proportion of 10% (that is, a metallic

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composite), and in the EDS spectrum (EDS – Energy Dispersive Spectroscopy) the chemical elements that make up the chemical composition of the metallic composite can be observed (Figure 10 b). Overall, the structure of the metal composite is normal, free of structural defects.

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 causes of modification the properties, and the tribological phenomena characteristics (friction and wear).

Technical specifications of commercially available frictional materials present the tribological and mechanical properties, indications regarding temperature effects, and operating recommendations.

The COF of frictional materials depends on their microstructure and composition, and users and manufacturers use those that consider them useful (COF being a starting parameter in the design of the braking system). The friction temperature modifies COF and it depends on the materials specifications in contact and can only be evaluated by testing any friction material.

Some complex problems encountered in the braking system field were solved by metallographic and chemical analysis of the brake pads, respectively the determination of their tribological and mechanical properties.

By the metallographic analysis of the pad material, no material faults in the structure were found. EDS analysis was also required to determine the elemental composition of the sample material, identify the component elements, and quantify the number of elements present in the analyzed material.

From the EDS analysis by elemental mapping for a reliable chemical characterization, it was found the existence of a big number of chemical elements in the composition of the pad material. To highlight the crystalline structure, the metallographic attack was used with Ni 4%, because the nature of the material was not known. It was noticed a normal structure and without faults, of the pad material.

For a complete analysis, some mechanical properties at the compression and bending stress were also measured, having a high resistance in a perpendicular direction in both situations (cases). Also, the sliding resistance in the perpendicular direction is much bigger, than what has in the parallel direction.

This is desirable, because it gives the pad good tribological behavior (high coefficient friction and minimal wear), so an extension of the life span.

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

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References

[1] W. Post, Cap: Car braking systems, în book: Brakes, Brake Control and Driver Assistance Systems, Ed. Konrad Rief, Springer Vieweg ©Springer Fachmedien Wiesbaden 2014, DOI10.1007/978–3–658–03978–3.

[2] N.N.B.Siti, M N.A.H.uhammad, N.M.S.Shahril, N. Mohd and S.O.Mohd, Cap: Analysis of Drum Brake System for Improvement of Braking Performance, in book: Engineering Applications for New Materials and Technologies, Ed. Springer International Publishing 2018, pp. 345–357

[3] E. Denimalab, J–J. Sinouac and S. Nacivet, Influence of structural modifications of automotive brake systems for squeal events with kriging meta–modelling method, Journal of Sound and Vibration vol. 463, 2019, Article 114938

[4] N. Borivoj, M. K.ila, S. Sanja, V. Marko and B. Sladjana, The Importance of Application and Maintenance of Braking System in Modern Automobile, VI International Conference Industrial Engineering and Environmental Protection, Zrenjanin, Serbia, 2016.

[5] E. Denimalab, J–J. Sinouac, S. Nacivet and L. Nechak, Squeal analysis based on the effect and determina.tion of the most influential contacts between the different components of an automotive brake system, International Journal of Mechanical Sciences, vol. 151, 2019, pp. 192–213

[6] H.F. Ganji and G.D. Ganji, Effects of equilibrium point displacement in limit cycle oscillation amplitude, critical frequency and prediction of critical input angular velocity in minimal brake system, AIP Advances, vol. 7(4), 2017, Article 045102

[7] S. Ebrahimi–Nejad and M. Kheybari, Brake System Design for Sports Cars using Digital Logic Method, International Journal of Automotive Engineering, vol. 7(4), 2017, pp. 2570–2582

[8] A. Phatak and P. Kulkarni, Drum Brake Backplate Analysis and Design Modification to Control Squeal Noise, International Journal of Engineering Development and Research, vol., 5(3), 2017, Article 1703131, pp. 920–928, http//www.ijedr.org.

[9] K. Shin, M. Brennan, J–E. Oh and C.J. Harris, Analysis of disc brake noise using a two–degree–of–freedom model, Journal of Sound and Vibration, vol. 254(5), 2002, pp. 837–848

[10] K. Shin, J–E. Oh and M. Brennan, Nonlinear Analysis of Friction Induced Vibrations of a Two– degree–of–freedom Model for Disc Brake Squeal Noise, JSME International Journal Series C, vol. 45(2), 2002, pp. 426–432
[11] M. Paliwal, A. Mahajan, J. Don, T.P. Chu and P. Filip, Noise and vibration analysis of a disc brake system using a stick slip friction model involving coupling stiffness, Journal of Sound and Vibration, vol. 28(3), 2005, pp. 1273–1284
[12] F.H. Yang, W. Zhang and J. Wang, Sliding bifurcations and chaos induced by dry friction in a braking system, Chaos, Solitons & Fractals, vol. 40(3), 2009, pp. 1060–1075
[13] X.P. Shen, Reduced noise – enhanced composite friction blocks, CN103216554A, 2013.
[14] E. Gao and B.W. Song, Process for producing metal base sintered friction sheet, CN1994628, 2007.
[15] D. Wei, J. Song, Y. Nan and W. Zhu, Analysis of the stick–slip vibration of a new brake pad with double–layer structure in automobile brake system, Mechanical Systems and Signal Processing, vol. 118, 2019, pp. 305–316
[16] F. Talati and S. Jalalifar, Analysis of heat conduction in a disk brake system, Heat and Mass]Transfer, vol. 45(8), 2009, pp. 1047–1059
[17] ***, How To Differentiate Braking Systems In Automobiles? Available: https://drivinglife.net/differentiate–braking–systems–automobiles/.
[18] H. Heisler, Brake system, în Advanced Vehicle Technology (Second Edition), Elsevier, Butterworth–Heinemann, 2002, pp. 450–509, ISBN: 9780750651318.
[19] P.R. Childs, Mechanical Design Engineering Handbook, Cap. 13: Clutches and Brakes, Butterworth–Heinemann is an imprint of Elsevier, 2014, pp. 513–564
[20] I. Hutchings and P. Shipway, Cap. 9: Applications and case studies, in Tribology. *Friction and Wear of Engineering Materials* (Second Edition), Butterworth–Heineman is an imprint of Elsevier, 2017, pp. 303–352, https://www.elsevier.com/books–and–journals.
[21] A. Day, Cap. 5: Brake Design Analysis în Braking of Road Vehicles, Oxford: Butterworth–Heinemann, 2014, pp. 97–148
[22] A.C. Cristescu, Studies and Research on Improving the Tribological Performance of Automobile Braking Systems: Research Report II, Polytechnic University of Bucharest, Bucharest, Romania, 2020 (In Romanian).
[23] F. Ilie and A.C. Cristescu, Tribological Behavior of Friction Materials of a Disk–Brake Pad Braking System Affected by Structural Changes – Review, Materials, vol. *15*(14), 2022, Article 4745
[24] A. Day, Cap.2: Friction and Friction Materials în Braking of Road Vehicles, Oxford: Butterworth–Heinemann, 2014, pp. 9–34

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