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EFFECT OF THE ALLOYING ELEMENTS ON THE PROPERTIES OF GRAY CAST IRON USED FOR AUTOMOTIVE BRAKE DISCS

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Over time, the automotive industry has undergone transformations, in either of technologies or materials used in the composition of vehicles, in order to ensure safety and comfort of passengers. Thus, special attention is paid to the braking system of vehicles and the materials it is made of. This paper presents the comparative analysis of two types of experimental cast iron alloyed with Cu and Mo, used in the manufacture of brake discs. In this respect, the physico-chemical and microstructural properties are shown, as well as the mechanical and tribological tests carried out. The results are compared to those obtained when using a brake disc made of a standard cast iron. The experiments performed lead to the improvement of the physical-mechanical and tribological properties of the steels intended for the production of brake discs. Thus, at the same percentage of Cu but a higher percentage of Mo led to an increase in hardness, mechanical strength and wear resistance.

Keywords: alloyed cast iron, iron-making, graphite, disc, brake, properties

1. Introduction

The automotive has transformed and will continue to change human’s mobility in the future. In the last period, the automotive engineering safety was considered the number one priority in the development of a new vehicle. In this context, the braking system of vehicles is the key element in ensuring the traffic safety, being made of several components that actively or passively contribute to increasing performance in operation [1]. All vehicles, regardless of destination, size and mode of propulsion use braking systems [2].

The vehicle braking systems are equipped with brakes with friction on each wheel: disc brakes are used on the front axle and disc or drum brakes are used on the rear axle [1], [3]. The need to extend the use of disc brakes on both axles of the motor vehicles is explained by the many advantages they have over the drum brakes. These advantages refer to: stability in operation at low and high temperatures, low sensitivity to the variation of the friction coefficient, uniform

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pressure distribution on the friction surfaces, uniform wear of the brake pads, large cooling surface and good conditions for heat dissipation [3].

During the vehicle braking process, the pressure in the hydraulic circuit has values between 2 MPa to 4 MPa, and the friction between the disc and the brake pad causes the temperature in the contact area to reach 700-800 °C in a very short time (an overheating occurs) [1], [4], [5]. This overheating of the brake disc can have serious consequences, reducing the safety of the braking system [1], [4]. Due to these simultaneous actions (thermal and mechanical), applied cyclically, the brake disc wears out. Therefore, under real operating conditions, the brake disc is subjected to a stress of thermo-mechanical fatigue [5]. For this reason, the materials used to make brake discs must have good thermal conductivity and high diffusivity. The materials used for the manufacture of brake discs must also have an appropriate friction coefficient, stable mechanical properties at high temperatures in a dry and humid environment, as well as high wear resistance [1], [4], [5].

Theoretically, there are several materials that can meet these requirements, ensuring a high performance in vehicle braking. Various ferrous materials, titanium-based materials, ceramic materials and aluminium metal matrix composite materials have been tested by now to make brake discs [2]. However, despite the evolution over time of the materials used for making brake discs, these ones are still made of cast iron, because the cast iron is the most technologically and economically efficient material, which provides all the necessary properties for the components of the vehicle braking system [1].

The types of cast iron used for brake discs have been studied by numerous researchers, for many decades. Thus, the research on cast iron brake discs has shown that the grey cast iron with lamellar, nodular and vermicular graphite is the most commonly used material [1], [5], [6] due to the adequate conductivity and thermal diffusivity properties [5], [7], [8]. Therefore:

- the grey cast iron with lamellar graphite has a good thermal conductivity due to the graphite in form of interconnected flakes, arranged as micro-plates, which enable good heat dissipation. The nodular graphite cast iron has a lower thermal conductivity than the one with lamellar graphite, because the graphite nodules are not connected to each other, while the vermicular graphite grey cast iron has thermo-mechanical properties located in-between;
- the thermal conductivity of the cast iron is proportional to the surface occupied by the graphite nodules;
- the thermal diffusivity of the grey cast iron is influenced by the equivalent carbon.

The improvement of the grey cast iron properties was obtained by increasing the carbon content or the equivalent carbon (EC). Thus, an increase with 0.40% of the equivalent carbon led to an increase with 25% of the brake disc diffusivity [9].

The literature indicates that the microstructure aspect of the grey cast iron is influenced by the variation of the carbon amount, estimated by the equivalent carbon and the cooling rate, and the percentage value of the friction coefficient increases with increasing area occupied by graphite in the base metal mass [5], [10].

In this context, Rhee and collaborators pointed out that a change in the chemical composition of the brake disc strongly affects both mechanical properties and wear limits [11] and Libsch & Rhe have shown that small changes in the alloying elements are changing the wear limits of the brake disc [12].

Recently, the manufacturers of cast iron for brake discs started to use Mo and Nb as alloying elements. These types of cast iron have high thermal conductivity and low temperatures in the friction zone, between the disc and the plate, but their high dimensions and weight are disadvantages [5].

There are also important the experiments, in which grey cast iron with addition of Cr, designed to make brake discs for vehicles, was produced, tested and validated [2]. The Cr alloying was taken into account anticorrosive properties and the anti-graphitizing effect of this element, which increases the number of eutectic cells and the proportion of perlite in the grey cast iron, which leads to improved properties of the cast iron.

The main objective of this paper is to make and characterize, from physico-chemical, microstructural, mechanical and tribological points of view, two types of cast iron, alloyed with both Cu and Mo, intended to make brake discs for motor vehicles. The results will be compared to those obtained in the case of a brake disc made of a standard cast iron, ASTM A159-83(2020).

2. Materials and methods

2.1 Materials

In order to improve the properties of the grey cast iron commonly used in the construction of brake discs, it was decided to alloy them with Cu and Mo. In order to carry out the experiments, were used brake discs made of cast iron, mark G2500 according to the ASTM A159-83(2020) standard. According to this standard, G2500 cast iron is intended for producing brake discs for vehicles. These were used to make two cast iron grades (F1 and F2), in which Cu and Mo were introduced as alloying elements. Cu has been introduced as an alloying element because it has a favorable influence on the wear resistance, even at a low content. This can be explained, on the one hand, by its submicroscopic separations and, on the other hand, by the reduction of the base metal mass oxidation, its action manifesting itself especially at sliding friction [6].

Cu is also a light graphitizing element and contributes to the development of perlite, which leads to the increase of tensile strength and hardness [13]. Mo acts as a carbide stabilizer, whose effect is the increase of hardness and mechanical strength due to the transformation of austenite into perlite [13]. Finally, the association of the elements Cu and Mo has a favorable action on machinability, leading to the increase of the cast iron structure homogeneity [6].

2.2 Producing experimental cast iron

The experimental types of cast iron, F1 and F2, were made in laboratory, in an induction furnace, with the capacity of 10 kg, were made of grey cast iron brake discs, the melting time being 90 minutes. After melting, the melt was poured into a pattern mould and in cylindrical moulds. The cooling was made in air for 12 hours, after which the test specimens were extracted. The pattern mould enabled obtaining the pins required by the tribological facility for the study of friction and wear, and the cylindrical moulds enabled obtaining discs with the diameter of 96 mm. Specimens were made of the brake discs initially considered, in order to determine the chemical composition, microstructure, mechanical and tribological properties of the standard cast iron, which will be further compared to the properties of the two newly obtained types of cast iron.

2.3 Characterization methods

The determination of the physico-chemical properties of F1 and F2 cast iron grades referred to the determination of the chemical composition and the measurement of the hardness of these alloys. The Brinell hardness test was performed in accordance with the Standard EN ISO 6508:2002, on disc specimens whose surfaces were flat, free of oxides and impurities, made of standard, F1 and F2 cast iron types. The microstructural analysis of cast iron was performed by light microscopy, using an optical metallographic microscope with the magnification of 1x200. The mechanical properties of cast iron are one of the most important aspects took into account when selecting it for making brake discs. Thus, the tensile strength was determined using Zwick/Roell Z005 universal test equipment. The experiments were carried out at a loading speed of 20 mm/min, at the temperature of 22 °C and the dimensions of the specimens used in the tests were 50x50x35 mm.

The wear behaviour analysis for the standard cast iron and the two types of cast iron (F1 and F2) was carried out using a tribological facility that allows for determining the performance in dry friction regime, and the test method was “pin - on disc”, in sliding movement. The tests carried out took into account the roughness of the material surface and the characteristics of the proposed experiment. Thus, the samples were previously mechanically processed and the roughness value after five measurements is Ra = 3.2μm, measured with a portable roughness meter model ISR-C002 with a resolution of 0.001 μm. All the samples used in the experimental facility had a diameter of 96 mm and were made either of standard cast iron or of the two cast iron grades, made in laboratory, F1 and F2. The cylindrical pins used in the experiments had a diameter of 6.25 mm, a height of 25 mm, and were made of the same materials as the discs. In laboratory experiments, the discs had the role to simulate the behavior of the brake disc in the whole braking system of the vehicles, and the pins played the role of brake pads. The tribological experiments were performed for average pressure of 1 MPa, 2 MPa and 4 MPa, applied to the pins by means of a normal load, at a sliding speed of 3.92 m/s. The pressure was applied in 200 cycles, each cycle involving the loading with the corresponding pressure for 1 minute, after which the specimen in the facility was left to rotate without loading for 3 minutes. The behavior assessment of the tested cast iron was done using the gravimetric method, by mass losses determined after the completion of a test cycle for both triboelements. Finally, the specific wear was calculated for each type of cast iron. During these experiments, the evolution of the thermal field near the contact area of the friction torques will be analyzed with a FLIR "Therma CAM Quick View" thermographic camera that allows to download images from an infrared camera to a PC, as well as capture images remotely in the camera. The captured images can provide information on the evolution of the temperature on contact periphery between the pin and the disk.

3. Results and discussions

3.1 Physicochemical and mechanical characterization

In order to develop F1 cast iron in the furnace were introduced 1769 g of standard cast iron: 45 g coke, 5g FeS, 14g FeMn, 5g FeP, 25g FeMo and 46g FeCu. For the elaboration of F2 cast iron in the induction furnace were introduced: 1495 g gray cast iron standard, 60 g coke, 18g FeMn, 5gFeS, 5g FeP, 55g FeMo and 30g FeCu.

In order to determine the chemical composition of the standard, F1 and F2 types of cast iron, five measurements were done for each specimen, the average values being shown in Table 1.

Table 1

Chemical composition of the cast iron made in laboratory

Cast iron	C [wt]	Si [wt]	Mn [wt]	P [wt]	S [wt]	Cr [wt]	Ni [wt]	Cu [wt]	Mo [wt]	CS [wt]	EC [wt]
F1	3.48	2.09	0.77	0.27	0.2	0.1	0.07	1.00	0.22	0.97	4.28
F2	3.56	2.09	0.87	0.27	0.2	0.1	0.07	1.00	0.46	1,01	4.40
Standard	3.28	2.4	0.6	0.2	0.15	0.18	0.08	-	-	0.94	4.13

The results of the chemical analyses revealed the following aspects.

-The standard cast iron taken from the original brake disc corresponds in terms of composition to the grade G 2500, according to ASTM A159-83(2020).

- The two types of cast iron, made in laboratory (F1 and F2) have carbon contents higher than the standard cast iron; this is explained by the addition of coke, which is a carburizing element.

- The Si, P, S, Cr and Ni contents are approximately close to those of the standard cast iron, with a growth of the Mn content, which helps to improve tribological behavior in the cast iron types F1 and F2; this is explained by the introduction of FeMn into the charge.

- The cast iron types F1 and F2 have the same degree of alloying with Cu and different degrees of alloying with Mo.

- The degree of carbon saturation (CS) shows that the standard cast iron and the F1 cast iron are hypoeutectic, while the F2 cast iron is eutectic.

- The equivalent carbon (EC) has the highest value for the F2 cast iron, with a significant increase compared to the standard cast iron.

For the Brinell hardness test the average values determined for each cast iron are shown in Fig. 1.

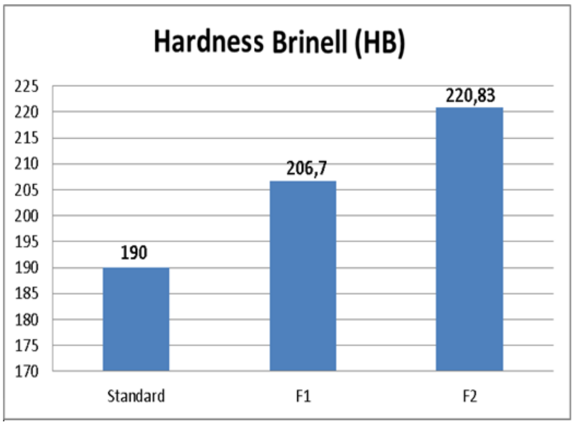


Fig.1. Brinell hardness average values for F1 and F2 types of cast iron versus the standard cast iron

According to the diagram shown in Fig. 1, the hardness values found for F1 and F2 are higher than those found for the standard cast iron; this is caused by the higher carbon content and the alloying with Mo and Cu (both elements play a role in the hardness increase). The increase of the S content in F1 and F2 (0.2%) also contributes to the increase of the hardness due to its anti-graphitizing action. The values of the mechanical tensile strength are shown in Fig. 2.

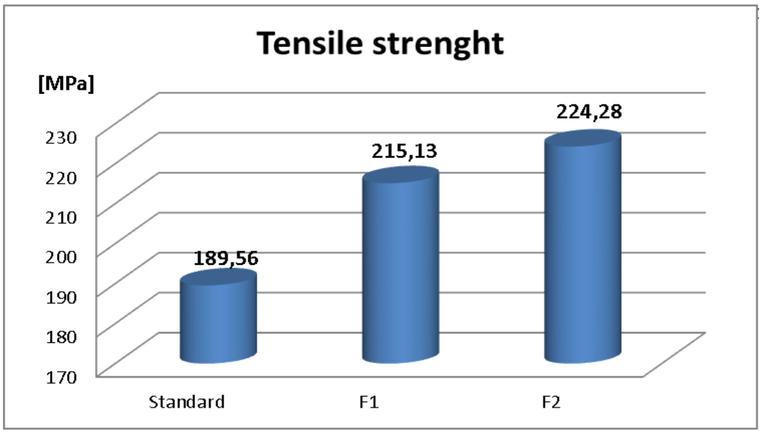


Fig.2. Mechanical tensile strength values for the standard, F1 and F2 types of cast iron.

Fig. 2 shows an increase in mechanical tensile strength for F1 and F2 as compared to the standard cast iron. This is due to the elements Cu and Mo, which confirms the research conducted so far, presented in the literature [6], [13].

3.2 Microstructural characterization

The microstructure of the standard cast iron in the brake disc is shown in Fig. 3. This is a grey cast iron, with interdendritic lamellar graphite of subcooling, type D, of small size (Gl4, Gl5). The structure is ferritic-perlitic, the surface occupied by perlite is about 65%, and the appearance of interdendritic cooling graphite of type D is accompanied by ferrite.

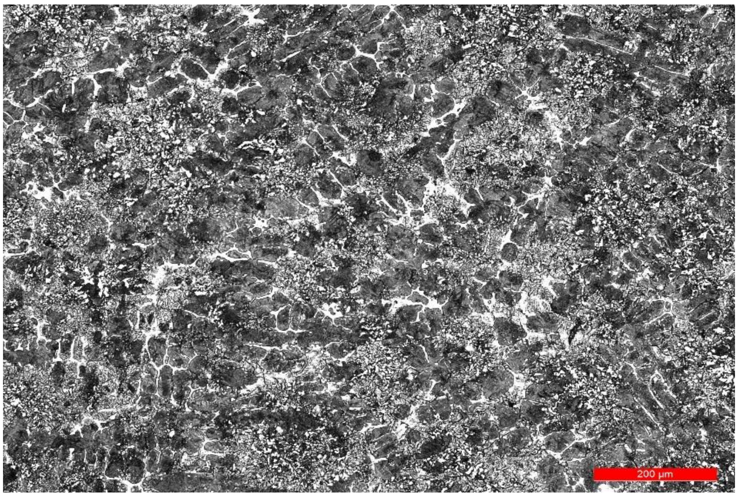


Fig.3. Microstructure of original disc brake magnified by 200x

The microstructures of the disc brakes made in laboratory are shown in Fig. 4 and Fig. 5, at magnification of 200x.

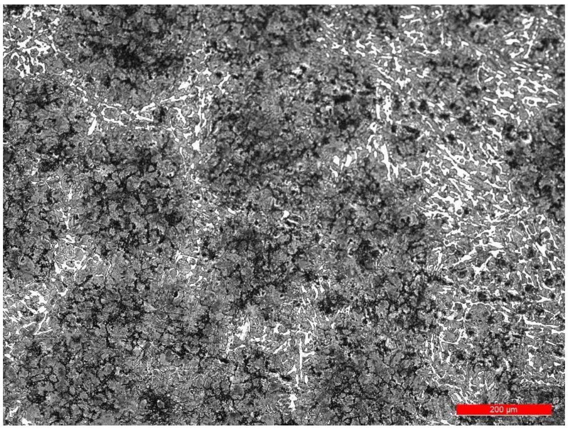


Fig.4. Microstructure of manufactured disc brake F1, magnified by 200x

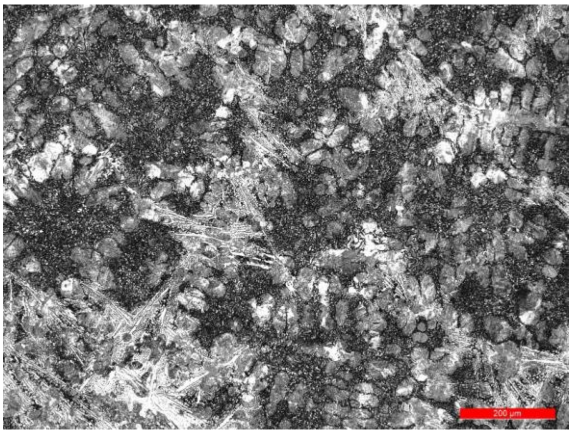


Fig.5. Microstructure of manufactured disc brake F2, magnified by 200x

For F1 (Fig. 4), the shape of graphite is semi-arched lamellar, associated with vermicular graphite (Gf1-Gf3), with length of Gl4-Gl5 type and the surface occupied by graphite separations of G8 type (over 5, up to 10%). The structure is ferritic-perlitic and the surface occupied by perlite is over 80%. The perlite has a dispersion degree (fineness) of type Pi 1.4, respectively 1.3-1.6 μm, in the case of medium lamellae (interlamellar distance). Also, the phosphorous ternary eutectic is present (arranged in the form of isolated separations and in the form of a discontinuous network) of E2 type (the surface occupied by the phosphorous eutectic being 2000-10000 μm^2 in the basic metal mass).

The grey cast iron F2 (Fig. 5) has a ferritic-perlitic structure, the surface occupied by perlite being over 85%. The graphite shape is punctiform interdendritic, associated with lamellar Gf5-Gf6, with small lengths Gl1-Gl3.

According to the dispersion degree, determined by the interlamellar distance, the perlite is of type Pi 1.4 (medium lamellae of 1.3-1.6 μm).

Unlike the standard cast iron, a development of the pearlitic structure is seen in F1 and F2. Also, it can be seen the finishing of the structure and the modification of shape and graphite distribution, thanks to Cu and Mo alloying elements. On the other hand, Mn and S have a perlitizing action at the eutectoid transformation, favouring the austenite transformation into perlite, leading, therefore, to the increase of its dispersion degree.

3.3 Tribological characterization

For the analysis of the wear behaviour, the disc specimens made of standard, F1 and F2 types of cast iron were checked with penetrating liquids. These checks revealed no cracks on the surface of the disc specimens. The specimens were also subjected to ultrasound checks, which also demonstrated the lack of inclusions and porosity inside them. Table 2 shows the wear of the cast iron discs, as well as the temperatures on the periphery of the contact between the pins and the disc at the end of tests, for each applied pressure. For each pressure applied, three sets of experiments were performed. The results in the table represent their arithmetic mean.

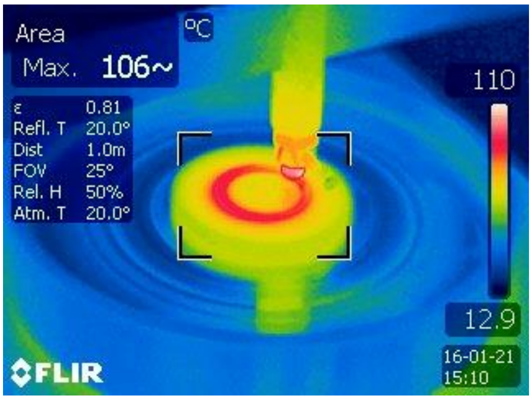
Table 2

Wear and temperature versus pressure and type of cast iron disc specimens

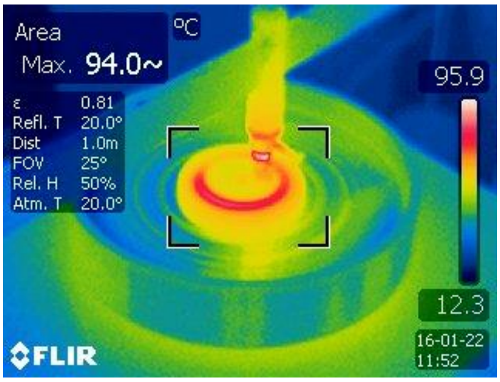
Cast Iron	1 [MPa]		2[MPa]		4[MPa]	
	Wear [g]	Temp [ºC]	Wear [g]	Temp [ºC]	Wear [g]	Temp [ºC]
Standard	0.20	75.8	0.35	116	0.79	228.9
F1	0.18	63.5	0.26	98	0.52	189.3
F2	0.17	58.6	0.24	89	0.48	179.4

Figure 6 shows the temperatures at the periphery of the triboelements in contact at the end of a set of experiments with a pressure of 2 MPa.

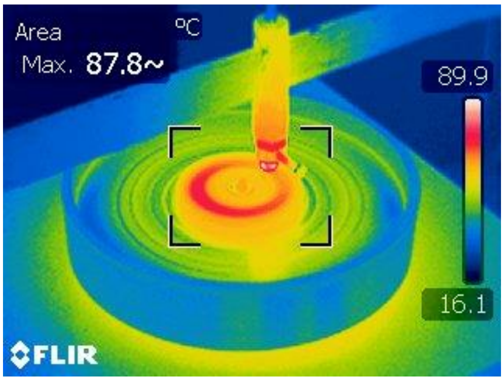
In Table 2 one can see that the cast iron wear decreases with increasing pressure. For low applied pressures (1 MPa), the three types of cast iron showed similar wear. At pressures higher than 2 MPa and, respectively, 4 MPa, the highest recorded wear was for the standard cast iron, followed by F1 and, then, by F2. The fact that the standard cast iron had the highest weight loss, in all test conditions, is explained by the fact that it had a lower amount of graphite than F1 and F2. Also, the high content of Si (2.40%) led to the maintenance of a ferritic-perlitic structure, the perlite occupying about 65%, and the ferrite being placed around the graphite flakes, which led to lower values of tensile strength and hardness of the standard cast iron [1], [6].



a-Standard cast iron



b-F1cast iron



c-F2 cast iron

Fig.6. Temperatures at the periphery of the elements' contact at the end of a set of experiments with a pressure of 2 MPa

The increase of F1 and F2 wear resistance is explained by their alloying with Cu (1%), which influenced the properties of the base metal mass (having a perlitizing role); this one, in combination with Mo, leads to increased wear resistance. The existence of graphite in F1 and F2 acts as a lubricant and protects the surface against wear. The wear resistance was calculated based on the experimental determinations performed for each test analyzed in the three load situations. The highest wear resistance for all applied pressures was found for the cast iron F2, which has the highest amount of Mo.

Regarding the pins used to carry out the tests, they register a minor change in mass compared to the disc, in all three loading cases.

In terms of heat transfer, the same cast iron F2 performed the best, the temperature determined at the end of each wear test having the lowest values. This is explained by the existence in its structure of punctiform interdendritic graphite associated with lamellar shapes, which led to increased heat transfer capacity. Also, a higher weight of the graphite volume leads to an increase in thermal conductivity, this being explained by the existence in the cast iron F2 of a double amount of Mo, which is a carbide stabilizer, improving the heat transfer capacity.

The temperatures recorded at the end of tribological tests for the types of cast iron made in laboratory (F1 and F2) were lower than for the standard cast iron. This shows a better heat transfer capacity, explained by the fact that Cu is a good conductor of heat.

According to the literature, the increase of equivalent carbon leads to increasing diffusivity of the cast iron, which is one of the ways to improve the heat transfer capacity [9]. This is confirmed by the fact that F2 has the highest equivalent carbon, followed by F1 and then by the standard cast iron.

4. Conclusions

The development of the automotive industry illustrates a growing trend towards increasing the car performance, while ensuring the safety and comfort of the passengers. The competitiveness in the automotive industry requires research and development of new materials and products able to ensure high operating parameters. Thus, a particularly important role is played by the knowledge about the properties of the materials used in the composition of vehicles, with a direct focus on the braking system, one of the key elements ensuring passenger safety.

Thus, as a result of the research and experiments on making cast iron alloyed with Cu and Mo intended to produce brake discs, the following conclusions can be drawn:

- Cu has a graphitization tendency, influences the shape and size of graphite and is a promoter of the pearlitic structure;
- Mo is a carbide stabilizer with a perlite refining role thanks to the transformation of austenite into perlite;
- the addition of Cu and Mo led to the development of a predominantly pearlitic structure;
- the increase of tensile strength and hardness is closely related to the pearlitic structure of the cast iron;
- the Brinell hardness values obtained for the cast iron made in laboratory are in accordance with the tensile strength and wear resistance and confirm the research carried out so far and presented in the literature;
- the existence of punctiform interdentritic graphite, associated with lamellar shapes, led to an increase in the heat transfer capacity of F2;
- both types of cast iron made in laboratory have a better wear behaviour than the standard cast iron.

In this context, it can be specified that Cu and Mo are complementary elements recommended in cast iron-making for the manufacturing of brake discs to be used for the braking systems of motor vehicles.

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