Research regarding the hardness of cast iron

F Bucur, A Socalici, A Josan and V Putan

Politehnica University of Timisoara, Department of Engineering and Management, 5 Revolution Street, Hunedoara, 331128, Romania

E-mail: flavius.bucur@yahoo.com

Abstract. Brake blocks for rolling stock are made of phosphorous cast irons or composite materials. In cast iron brake blocks, their structure and mechanical characteristics are influenced by their chemical composition. Through the research and experiments done, there have been established correlations between chemical composition and hardness. The correlations are presented both in analytical and graphical form, as well as their analysis from a mathematical and technological point of view. The regression areas allow the identification of the optimal areas of variation of the analyzed parameters.

1. Introduction

In the rail transport field, the braking system pays an important role. The brake installation includes the set of machines and devices fixed on the rail rolling stock, by the aid of which the train reduces speed or stops. The brake-block brake is the most commonly used type of brake for rolling stock. The poor quality of the braking system can lead to high maintenance costs and accidents [1].

The railway regulations and instructions impose the conditions of using the braking system, respectively the brake blocks, by specifying the way of assembling them on the system, the periodical check schedule and the moment of changing them. The friction coefficient and the usage intensity of the brake block represent the parameters by which the material is chosen. The friction coefficient, as functional measure, changes according to contact pressure and sliding speed, considered as work parameters of the exploitation regime, and according to temperature, as parameter derived from working conditions.

The mechanical characteristics and the composition of the materials used for manufacturing cast iron brake blocks for railway vehicles are regulated by the Specifications Sheet UIC 832 [2]. The quality of the brake blocks is guaranteed by the certification issued by AFER (Autoritatea Feroviară Română), the designated authority in this field in Romania. Each delivered brake block is AFER-certified, thus guaranteeing its quality and conformity. The technical quality conditions and the main measures for brake blocks made of P10 cast iron, used for motor and towed rail rolling stock with standard gauge, are specified in the tender specifications no.1/SFMR/SDT/2000/*Saboţi de frână pentru material rulant motor şi remorcat*, advised by AFER [3].

In manufacturing brake blocks for rolling stock, P10 cast iron is the most widely used type of material. Brake blocks usage is limited, their friction coefficient decreasing sharply during braking at high speeds, and their wear - due to jamming tendency - intensifying with the increase in temperature in the friction coupler [4].

The grey cast irons are perlite cast irons. In their structure we encounter a ternary phosphorous eutectic, called steadite, made of perlite, cementite and iron phosphide [5]. The main element that

influences the cast iron structure is carbon. Carbon is a graphitizing element, which expands the quantity of graphite in the gray cast irons and diminishes the quantity of perlite. The rise of carbon content leads to decreased mechanical resistance, hardness and endurance of the cast iron. Silicon is a highly graphitizing element, which increases the refraction property of the cast iron. Silicon increases the quantity of ferrite and graphite, decreases the quantity of perlite and, consequently, reduces the resistance and hardness of the gray cast iron. Manganese is a non-graphitizing element, which increases the quantity of perlite in the gray cast iron, respectively its mechanical resistance, hardness and wear resistance [5]. Sulfur is a non-graphitizing element, which determines the forming of interdendritic graphite, which in turn gives the cast iron heat proof qualities. Phosphorus is a poor graphitizing element during the first crystallizing of the cast iron, and a non-graphitizing element during the second crystallizing. It is found partially dissolved in ferrite, which it hardens, and partially as a ternary eutectic, called steadite. This eutectic improves the mechanical resistance, hardness, abrasive wear resistance and casting properties of the cast iron. [5-7]. The quantity of phosphorous eutectic in the cast iron depends directly upon the content of phosphorus, being also influenced by the factors which increase the tendency of segregation in the phosphorus. The nature of the materials used in the load as well as the needs of correction when obtaining phosphorous cast irons, significantly influence the sensitivity of the cast irons when forming their core porosity [6].

2. Experimental research

The industrial research was performed to determine correlations between the elements in the chemical composition of cast iron (considered as independent parameters) and the main quality parameter for brake blocks, which is hardness (considered as dependent parameter).

For the industrial research there have been observed a number of 70 charges of cast iron used to produce brake blocks (types S_1, S_2, LDH, LDE, LE). An important characteristic, with a high influence on the exploitation durability of the brake block, is hardness. For brake blocks, hardness is measured in five points, two found at the ends of the block and three through the cross section, according to Figure 1. The brake block needs to have, on the side surface, as well as in the cross section, a Brinell hardness of 197- 225 HB [3].
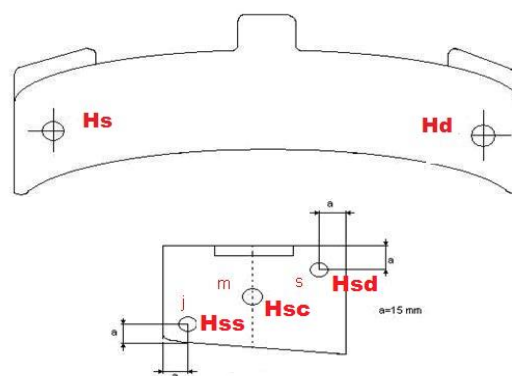

Figure 1. The points of measuring hardness [3]

For the analysis, the following notations have been used (according to Figure 1):
- Hs and Hd represent the hardness at the ends of the brake block, on its surface;
- Hss, Hsc and Hsd represent the hardness in the cross section, in three points, across the sectioned piece of a broken brake block during resilience testing – up, middle, down;
- (Hs+Hd)/2 hardness average on the brake block surface;
- (Hss+Hsc+Hsd)/3 hardness average in the cross section;
- the elements in the chemical composition (%C, %Mn, %Si and %P).

The experimental data has been processed in MATLAB software regarding the hardness of the phosphorous cast iron from which brake blocks are made and the chemical composition of the cast iron. There have been obtained equations of double correlation expressed as second-degree polynomial functions, both in graphical and analytical form. There are provided correlation equations, regression areas and level curves in Figures 2-7 with their corresponding equations (relations 1-6). In addition, for each correlation, the correlation coefficient and the coordinates for the inflection points are given.

3. Results

The resulting correlations are given in a graphical form only for the average obtained for the surface of the brake block and along its cross section.
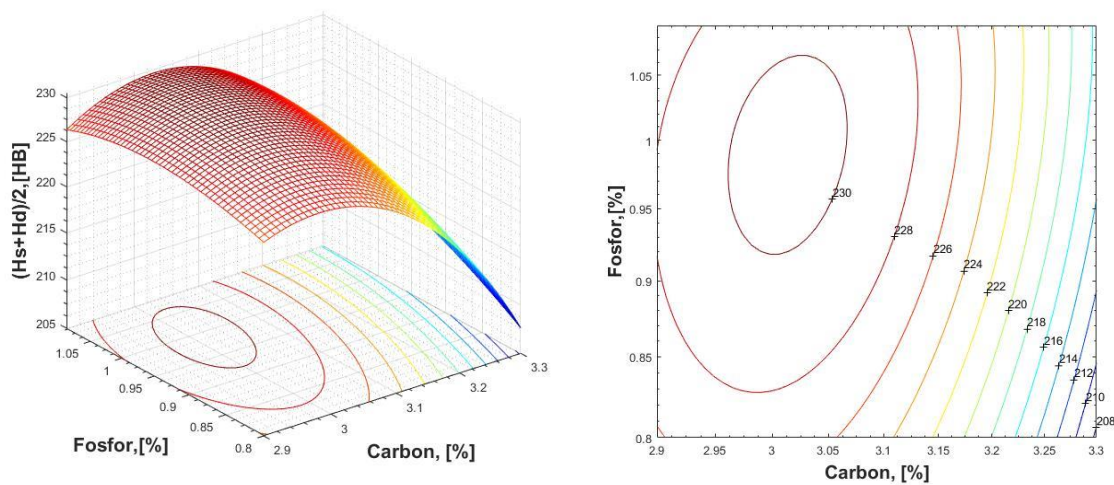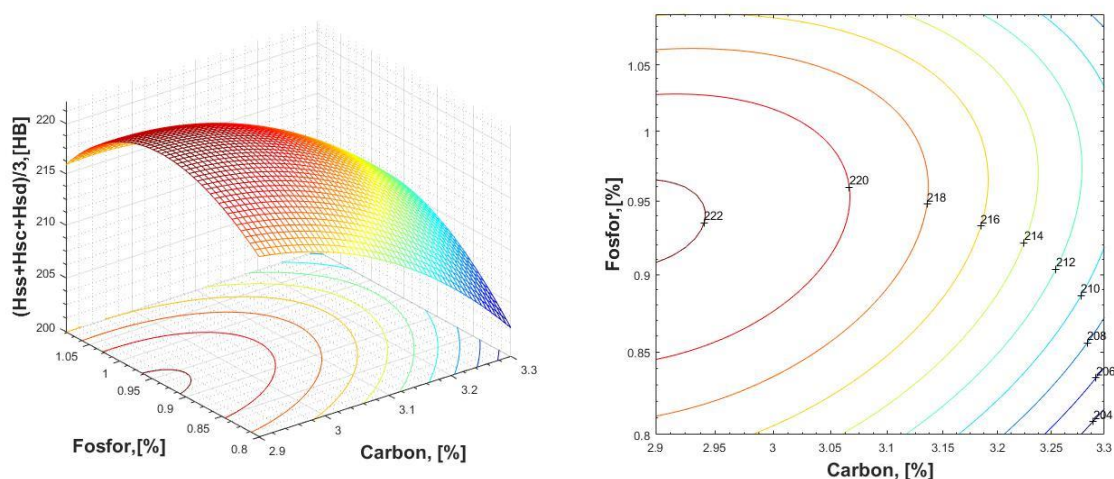

Figure 2. $(H_s+H_d)/2 = f(C, P)$

Figure 3. $(H_{ss}+H_{sc}+H_{sd})/3 = f(C, P)$

Correlation equations for hardness variation depending on the content of carbon and phosphorus are:

$$\frac{H_s+H_d}{2} = -0.19 \cdot C^2 - 0.09 \cdot P^2 - 0.06 \cdot C \cdot P + 1.09 \cdot C + 0.0017 \cdot P - 1.42 \tag{1}$$

Correlation coefficient: $R^2 = 0.57$.

Maximum point: $C = 3.014\%$; $P = 0.991\%$, $(HB_s+HB_d)/2 = 230.50$ HB.

$$\frac{H_{ss}+H_{sc}+H_{sd}}{3} = -67.20 \cdot C^2 - 267.72 \cdot P^2 + 52.48 \cdot C \cdot P + 338.15 \cdot C + 349.21 \cdot P - 427.99 \tag{2}$$

Correlation coefficient: $R^2 = 0.76$.

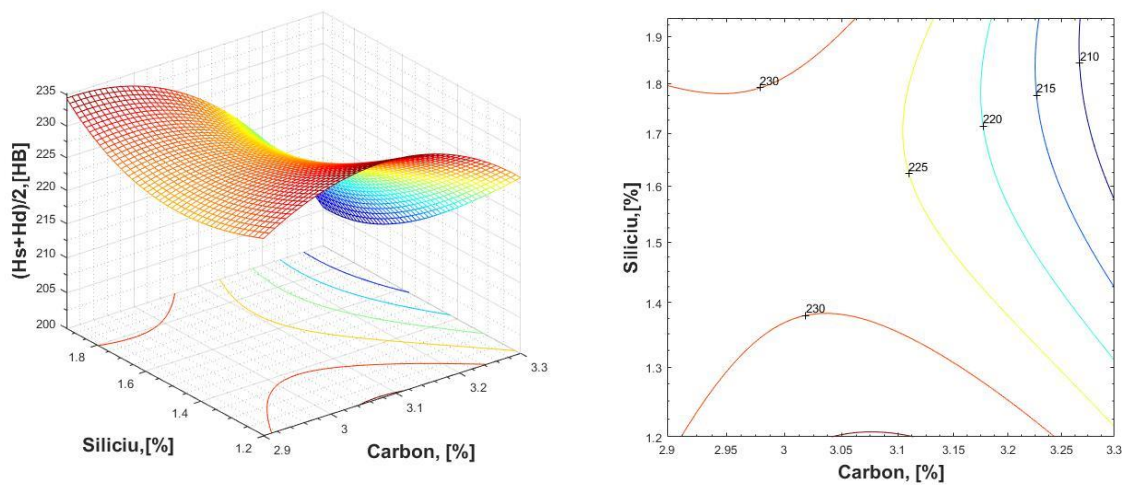Maximum point: $C = 2.88\%$; $P = 0.93\%$, $(H_{ss}+H_{sc}+H_{sd})/3 = 222.24$ HB.

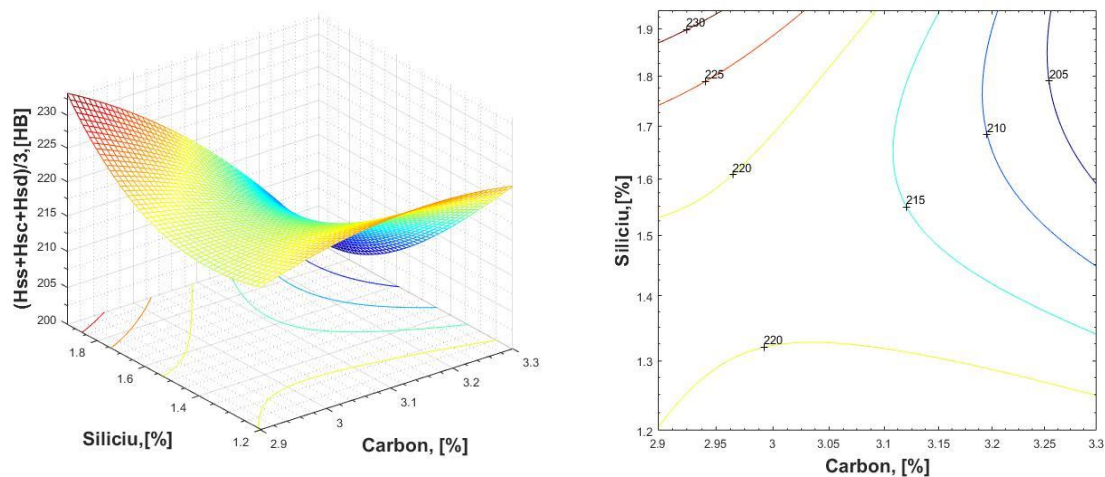**Figure 4.** $(H_s+H_d)/2 = f(C, Si)$

Figure 5. $(H_{ss}+H_{sc}+H_{sd})/3 = f(C, Si)$.

Correlation equations for hardness variation depending on the content of carbon and silicon are:

$$\frac{H_s+H_d}{2} = -0.19 \cdot C^2 + 0.03 \cdot Si^2 - 0.08 \cdot C \cdot Si - 1.27 \cdot C + 0.13 \cdot Si - 1.79 \tag{3}$$

Correlation coefficient: $R^2 = 0.59$.

Inflection point: $C = 2.99\%$; $Si = 1.58\%$, $(HB_s+HB_d)/2 = 228.04$ HB.

$$\frac{H_{ss}+H_{sc}+H_{sd}}{3} = -61.98 \cdot C^2 + 44.60 \cdot Si^2 - 121.50 \cdot C \cdot Si + 537.46 \cdot C + 230.38 \cdot Si - 735.11 \quad (4)$$

Correlation coefficient: $R^2 = 0.87$.

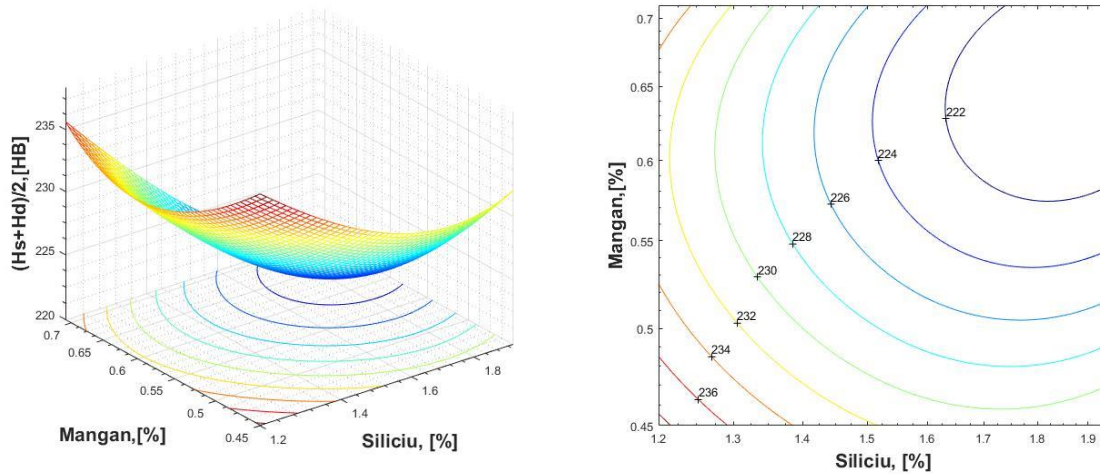Inflection point: $C = 2.94\%$; $Si = 1.42\%$, $(H_{ss}+H_{sc}+H_{sd})/3 = 219.04$ HB.

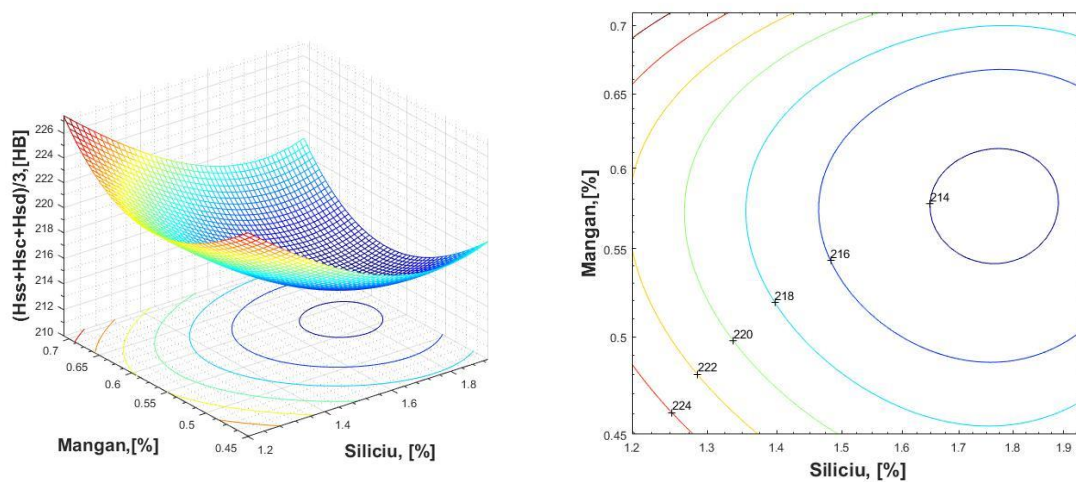**Figure 6.** $(H_s+H_d)/2 = f(Si, Mn)$

Figure 7. $(H_{ss}+H_{sc}+H_{sd})/3 = f(Si, Mn)$

Correlation equations for hardness variation depending on the content of silicon and manganese are:

$$\frac{H_s+H_d}{2} = 27.76 \cdot Si^2 + 262.81 \cdot Mn^2 - 42.89 \cdot Si \cdot Mn - 76.46 \cdot Si - 264.13 \cdot Mn + 379.03 \quad (5)$$

Correlation coefficient: $R^2 = 0.59$.

Minimum point: $Si = 1.88\%$; $Mn = 0.65\%$, $(HB_s+HB_d)/2 = 220.33$ HB.

$$\frac{H_{ss}+H_{sc}+H_{sd}}{3} = 25.50 \cdot Si^2 - 289.63 \cdot Mn^2 - 6.02 \cdot Si \cdot Mn - 86.76 \cdot Si - 323.57 \cdot Mn + 383.72 \quad (6)$$

Correlation coefficient: $R^2 = 0.87$.

Minimum point: $Si = 1.76\%$; $Mn = 0.57\%$, $(H_{ss}+H_{sc}+H_{sd})/3 = 213.62$ HB.

The metallographic examination (according to specification SR EN ISO 945-1:2009 and chart UIC 832) of the cast iron used for brake blocks consists in analyzing four samples:

- one sample for identifying the form of graphite segregations;
- one sample for determining the perlite configuration;
- one sample for the base metallic mass;
- one sample for the phosphorous eutectic.

Figure 8 presents the microstructures of the analyzed samples for brake blocks type S_1 produced for freight and passenger wagons, Figure 9 - for brake blocks type LDH for Diesel hydraulic engines, respectively Figure 10 - for brake blocks type LDE for Diesel electric engines.
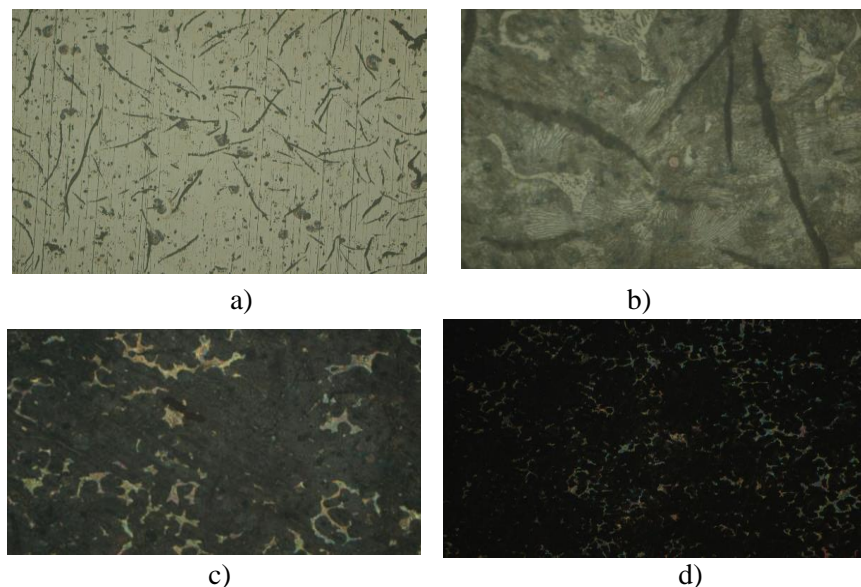

a)   b)

c)   d)

Figure 8 Microstructures of samples (brake block type S_1):
a) graphite, no attack, 100X; b) lamellar perlite, nital attack, 500X;
c) base metallic mass, nital attack, 100X, d) phosphorous eutectic, nital attack, 50X

The micro-structural analysis of the samples for the three given types of brake blocks highlights the following issues [8]:

- Considering the shape of graphite segregations, the graphite appears under the following forms:
  - linear lamellar, type Gf1 (for brake blocks type S1 and LDH);
  - linear lamellar, type Gf1 (80%) and semi-articulated lamellar, type Gf2 (20%), for brake blocks type LDE;
- Considering the repartition of graphite, it is encountered in the form of isolated segregations, type Gr1, for all three types of brake blocks;
- Considering the length of the graphite segregations, we observe:
  - lamellar graphite type Gl5 (60%) + Gl6(40%) – for brake blocks type S1;
  - lamellar graphite type Gl5 (80%) + Gl6(20%) – for brake blocks type LDE 16;
  - lamellar graphite type Gl5 – for brake blocks type LDH.
- Considering the surface occupied by the graphite, it can be placed within the structure type G10, for brake blocks type S1, respectively G6, for brake blocks type LDE and LDH;
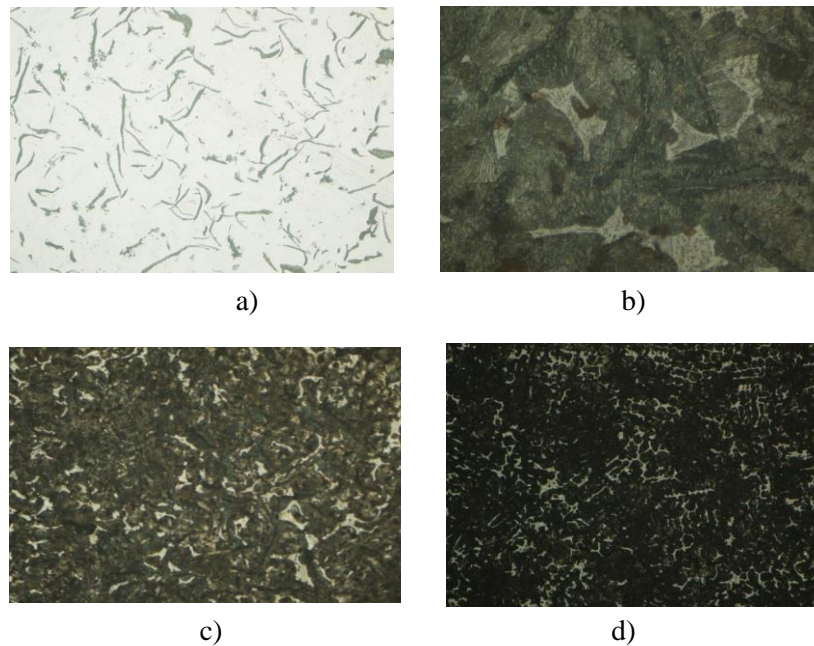
Figure 9. Microstructures of samples (brake block type LDE):
a) graphite, no attack, 100X; b) lamellar perlite, nital attack, 500X;
c) base metallic mass, nital attack, 100X, d) phosphorous eutectic, nital attack, 50X

Figure 10. Microstructures of samples (brake block type LDH):
a) graphite, no attack, 100X; b) lamellar perlite, nital attack, 500X;
c) base metallic mass, nital attack, 100X, d) phosphorous eutectic, nital attack, 50X
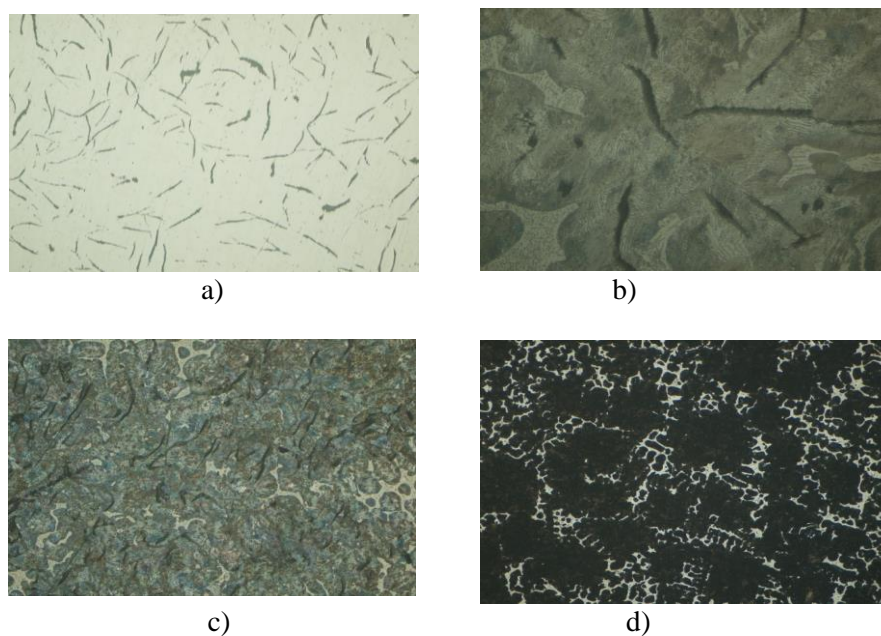
- The surface occupied by the perlite is well highlighted, the perlite lamellae being thin, and the ferrite proportion is under 5% (for S1 and LDH) and occurs under the form of isolated clumps;
- The phosphorous eutectic, separated interdendritically, has a lace-like shape, distributed for all three types of brake blocks; the phosphorous eutectic lattice is uniformly distributed, as follows:
  - Er2 – for brake blocks type S1;
  - Er3 - for brake blocks type LDE;
  - Er4 - for brake blocks type LDH.
- There have not been observed any areas of loose cementite for any of the types of brake blocks analyzed.

4. Conclusions

The quality of the parts which are cast at high density, but especially the quality of the surfaces and the dimensional precision are considerably higher than the ones obtained by any other classical method of molding.

The P10 phosphorous cast iron, of which brake blocks are made, is characterized by its capacity of maintaining the friction coefficient stable and by its high tear and heat resistance, preventing the elements in the friction coupler to get stuck (jammed), it has a high thermal conductivity and heat shock resistance.

After analyzing the regression areas and the double correlation equations, a number of conclusions can be drawn:

- The variation of independent parameters (chemical composition) within technological limits determines a variation for the dependent parameter (hardness), also within technological limits, with the latter being situated on a regression area or next to it;

- By intersecting the correlation areas with level planes, level curves were obtained, thus allowing setting the variation limits for the independent parameters in order to obtain a certain value for the dependent parameter;

- For each graphical representation, sub-domains can be identified, where it may be necessary to find the values for the dependent parameter, which determines, in fact, the variation limits for the independent parameters;

- For all the obtained correlations, the R^2 coefficient has values of over 0.5, which indicates that these correlations are significant and represent well the connection between hardness and chemical composition;

- For values of the hardness parameter found between 197 and 255 HB, the variation limits for the independent parameters are determined as follows: C = 2.95-3.2%, Man = 0.6-0.7%, Si = 1.45-1.95%, S = 0.06-0.09%; P = 0.85-1.0%, and residual elements preferably under 0.2%.

The hardness of cast iron brake blocks is influenced by chemical composition and structural components of the cast iron, and the obtained results are applicable in cast iron manufacturing of brake blocks destined for motor and towed rolling stock.

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