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Metallurgy of the Grey Cast Iron for the Automotive Parts

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The melt metal is a complex solution, which may contain for the production of high-quality grey iron a number of unsuitable elements. The molten cast iron contains areas enriched with carbon, higher amount of silicon in local areas, manganese, sulphur, and phosphorus. These elements can adversely affect the properties of the produced iron for the automotive industry. The oxygen activity, hardness, tensile strength, viscosity, chemical composition, and other physical and mechanical properties of cast iron are studied.

Key words: cast iron, carbon, hardness, oxygen activity, metallurgy, melting devices, brake disc.

Розтоплений метал є комплексним розчином для виробництва високоякісного сірого чавуну, який може містити ряд небажаних елементів. У розтопленому чавуні є області, збагачені вуглецем, велика кількість кремнію в окремих ділянках, манган, сірка та фосфор. Ці елементи можуть мати неґативний вплив на властивості чавуну, який використовується в автомобільній промисловості. Вивчено активність кисню, твердість, міцність на розтягнення, в'язкість, хемічний склад, а також інші фізичні та механічні властивості чавуну.

Ключові слова: чавун, вуглець, твердість, киснева активність, металурґія, топильні пристрої, гальмівний диск.

Расплавленный металл представляет собой комплексный раствор для производства высококачественного серого чугуна, который может содержать ряд нежелательных элементов. В расплавленном чугуне находятся

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области, обогащённые углеродом, большое количество кремния в отдельных участках, марганец, сера и фосфор. Эти элементы могут отрицательно влиять на свойства чугуна, используемого в автомобильной промышленности. Изучены активность кислорода, твёрдость, прочность на растяжение, вязкость, химический состав, а также другие физические и механические свойства чугуна.

Ключевые слова: чугун, углерод, твёрдость, кислородная активность, металлургия, плавильные устройства, тормозной диск.

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1. INTRODUCTION

Cast iron melt is a complex polycomponent solution. In terms of chemical composition of cast iron, solutions are characterized by high carbon content (up to 3.8%) and the content of silicon (up to 2.8%), manganese, sulphur and phosphorus. The high content of carbon and silicon-iron melt differs significantly from the molten steel in terms of physical properties (such as viscosity, surface tension and volume changes). Viscosity affects the property of flowability and, therefore, the iron mould filling by melt iron.

The viscosity of the molten cast iron may complicate the casting and slag flowing out (because of vaccination melt). Viscosity decreases with increasing melt temperature. Experiments showed that carbon and silicon significantly lower the viscosity and, thereby, improve the flowability of iron [1, 2]. Dynamic viscosity of lamellar graphite cast iron at 1310°C is $2.65\cdot10^{-3}$ $Pa\cdot s^{-1}$; the kinematic viscosity is $0.30\cdot10^{-6}$ $m^2\cdot s^{-1}$. With additions of alloying elements (Cu, Ni, W, V and Mn) of over 1% content, the viscosity usually decreases. Surface tension of lamellar graphite cast iron at 1300°C is 1.1 $N\cdot m^{-1}$. Volume changes are reflecting by changes of the specific volume. Flake graphite cast iron containing 3.5% C and 2.5% Si has a specific volume of 0.16 $cm^3\cdot kg^{-1}$; it is an increase in the specific volume of 9.3% [3, 4]. Molten cast iron structure described [5] according to the theory of chemical inhomogeneity due to added impurities.

2. CHARACTERISTICS OF THE MOLTEN METAL AND PROPERTIES OF MOLTEN CAST IRON

The molten cast iron contains areas enriched with carbon and carbon clusters. In addition, due to the higher amount of silicon in local areas of the melt, the crystals of SiC are formed. Near the SiC crystals, melt is rich on silicon. These areas are together with cluster formed nuclei for the crystallization of graphite. The formation of graphite nucleation occurs during the transition from the melt to the solid phase during eutectic crystallization. At this time, it must be provided with the necessary amount of free oxygen.

In foundry practice, it is introduced the notion of degree of oxidation of the melt $S = SiO_2/(FeO + Fe_2O_3 + MnO) = 0.4$ to 0.8. Lower values of this ratio causes shrinkage of the incident and harden. Higher values cause the occurrence of slag and endogenous bubbly in the casting. The solubility of oxygen in the melt depending on the temperature monitored [6] provides the reaction of oxygen:

$$(1/2)O_2 \rightarrow [O]. \quad (1)$$

Gibbs energy by the standard pressure is given by

$$\Delta G_T^0 = -28000 - 0.69T, \quad (2)$$

$$\log[O] = -\frac{1458}{T} - 0.0359, \quad (3)$$

where T—temperature [K].

The oxygen activity in the melt can be calculated:

$$a_0^0 = f_0[\%\ O], \quad (4)$$

where a_0^0—oxygen activity by standard pressure of [1], f_0—the activity coefficient of oxygen, [% O]—oxygen content in the melt.

Konecny *et al.* [7] indicates the specific activity values of oxygen depending on the temperature of cast iron with lamellar graphite; for a temperature of 1375°C, the oxygen activity is 0.75 ppm, and at temperature of 1450°C, it is 1.25 ppm.

Metallurgy iron depends on the type of melting device. For the production of automotive parts (brake discs, brake drums, pads combustion engine blocks and heads for internal combustion engines, piston rings), there is used medium frequency induction furnace with a frequency of 400–3000 Hz. Therefore, it is possible to use smaller batch lumpiness. Medium furnaces allow melt from solid feed the entire volume of the melt is poured into the ladle. This allows, for greater customization melting equipment, smelting process and instantaneous melt adapts to the needs of foundry, when melting in the industrial practice uses three options melting (synthetic and semisynthetic method, a reflow process). Some foundries use batch consisting of steel scrap, recovered material, pig iron, cast iron scrap and optionally chips from machining process castings. Chemical composition can be alloyed. Electric induction furnaces are ideal for melting iron with lamellar graphite that is intended for the production of automobile parts. Electric induction furnaces have a lining of the acidic refractory materials (in Czech Republic—Suracit). During the melting, the content of carbon, silicon, manganese and content of alloying elements are modified.

Burns of silicon and manganese depend on the oxygen content in the melt. At high carbon content in the melt, the silicon and manganese burn is negligible. During operation, induction furnaces are in practice often used for long-term maintenance of the melt temperature in the furnace. For long-term maintenance of the melt in the furnace, the oxidation reaction with the atmosphere and the reaction of carbon with silicon dioxide in the furnace lining may be carried out. The course of the intensity of these reactions depends on the temperature. At temperatures up to 1350°C, there are practically no changes in the chemical composition of the melt iron. At higher temperatures, the carbon and manganese are burned. At temperatures of 1450°C, the value of the burn carbon is to 0.20% per hour; by silicon and manganese, the change is slight. At temperatures higher than 1450°C, the silicon and manganese changes arise. During casting, it is important that the ladle were warmed to approximately 600°C.

3. EXPERIMENTAL PART

Monitoring of iron metallurgy manufacturing ventilated disks for the automotive industry is presented in Fig. 1.

The melt for the production of brake discs were prepared in medium-frequency induction furnace. It was assumed that it would be ready for production of melt iron EN GJL 250. It is believed that the melt for the production of brake discs should satisfy the chemical composition: 3.3% C, 1.8% Si, 0.7% Mn, 0.02% P, and 0.07% S. Since the brake disc often corrodes during operation, it is recommended to add still about 0.3% Cu. Eutectic degree of iron is 0.89.

It is assumed that the charge is used in steel scrap, pig iron, cast iron material and reversible cast iron waste.

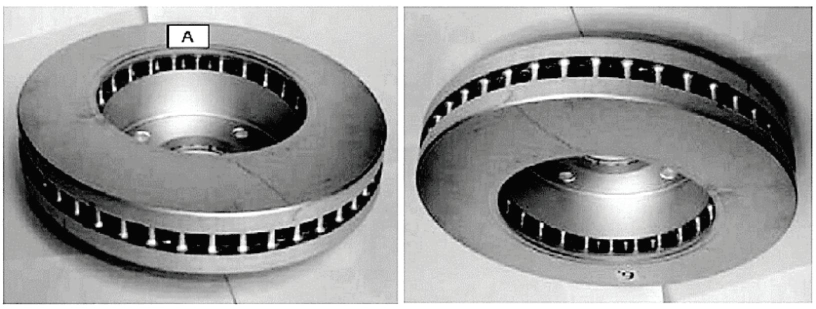

Fig. 1. Monitoring the production of ventilated brake discs.

For the production of iron melts, raw materials, which are listed in Table 1, were used.

3.1. Determination of the Carbon Content in the Molten Cast Iron

3.1.1. Calculus of Carbon in Cast Iron

Estimated carbon content in the cast iron is $C_{CI} = 3.3\%$.

Carbon in charge is:

$$C_{CH} = \frac{10 \cdot 0.2 + 25 \cdot 4.2 + 28.8 \cdot 3.2 + 35 \cdot 3.19}{10 + 25 + 35 + 28.8 + (0.5 + 0.2 + 0.5)} = 3.11\%. \quad (5)$$

It must be added carbon: $\Delta C = C_{CI} - C_{CH}$ (3.3 − 3.11 = 0.19). It will be delivered through a special coke:

$$w_{SC} = \Delta C \frac{100}{\eta_C} = 0.19 \frac{100}{75} = 0.26 \text{ kg}. \quad (6)$$

3.1.2. Proposal of Content Individual Component and Convert Chemical Composition

Content is as follow: 10% steel waste, 35% cast iron waste, 29% returnable material, 25% pig iron, 0.5% FeSi75, 0.2% FeMn80, 0.3% copper.

TABLE 1. Summary of raw materials for the production of cast iron with lamellar graphite.

Raw material	Sum of batch, %	Carbon content, %	Silicon content, %	Manganese content, %	Phosphorus content, %	Sulphur content, %
Steel waste	10	0.2	0.5	0.4	–	–
Pig iron M1	25	4.2	1.2	0.8	0.08	0.15
Recovered material	28.8	3.2	1.65	0.6	0.10	0.08
Cast iron waste	35	3.19	1.70	0.6	0.02	0,09
FeSi75	0.5	–	75	–	–	–
FeMn80	0.2			80		
Cu (100%)	0.3	For corrosion resistant castings				

Note: For calculus, elements are selected. For cast iron, it is assumed C/Si = 1.8.

Control composition of silicon:

$$\mathrm{Si} = \frac{10\cdot 0.5 + 25\cdot 1.2 + 28.8\cdot 2.0 + 35\cdot 2.2 + 0.5\cdot 75}{10 + 25 + 35 + 28.8 + (0.5 + 0.2 + 0.5)} = 1.66\%. \quad (7)$$

Control composition of manganese:

$$\mathrm{Mn} = \frac{10\cdot 0.4 + 25\cdot 0.8 + 28.8\cdot 0.8 + 35\cdot 0.60 + 0.2\cdot 80}{10 + 25 + 35 + 28.8 + (0.5 + 0.2 + 0.5)} = 0.78\%. \quad (8)$$

Control composition of phosphor:

$$\mathrm{P} = \frac{25\cdot 0.08 + 28.8\cdot 0.1 + 35\cdot 0.02}{10 + 25 + 35 + 28.8 + (0.5 + 0.2 + 0.5)} = 0.06\%. \quad (9)$$

Control composition of sulphur:

$$\mathrm{S} = \frac{25\cdot 0.15 + 28.8\cdot 0.08 + 35\cdot 0.09}{10 + 25 + 35 + 28.8 + (0.5 + 0.2 + 0.5)} = 0.09\%. \quad (10)$$

The smelting is carried out as necessary adjustment of the metal charge. The vaccination of the melt the master alloy was used in an amount FeSi75 0.4% wt. of melt. Some manufacturers of automotive parts are used for preparing of the melt also molybdenum. It is very important alloying element but it is expensive. Significantly, refines of pearlite structure reduces the sensitivity to cooling rate, increases the strength and stabilizes the structure at high temperatures.

If there is more phosphorus in cast iron, molybdenum supports the creation of Steadite.

3.2. Monitoring of the Activity of Oxygen

To determine the oxygen activity in molten iron, the method for measuring electromotive voltage (*EMV*) on the galvanic cell is currently used, where a solid electrolyte is a refractory oxide, exhibiting ionic conductivity. Part of the oxygen concentration is further article reference substance with a known amount of oxygen activity. Scheme of measuring probe for determining the electromotive voltage is shown in Fig. 2.

Oxygen activity value of reading *EMV* and temperature can be determined based on the equation, which is recommended by the manufacturer in the Czech Republic probes (Thermocouples Kladno) and have been prepared on the ČSAV at workplace Ostrava:

$$\log(a_{\mathrm{O}}) = 4.516 - \frac{13272.4 - 10080(EMV + 0.025)}{T}, \quad (11)$$

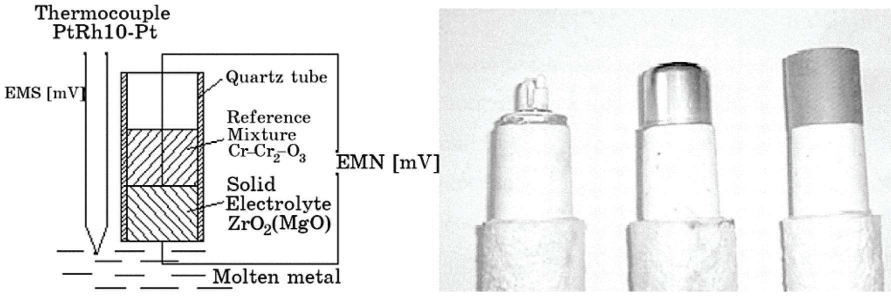

Fig. 2. Scheme of probe for measuring temperature and oxygen activity in the melt cast iron.

TABLE 2. Measured values of the *EMV* and calculated oxygen activity.

Activity of oxygen in the metal molten			
Member of measurements	Temperature, °C	*EMV*, mV	Oxygen activity, ppm
1	1492	–153	$1.86 \cdot 10^{-4}$
2	1448	–146	$1.26 \cdot 10^{-4}$
3	1395	–133	$8.13 \cdot 10^{-5}$
4	1352	–101	$7.59 \cdot 10^{-5}$
5	1306	–77	$5.62 \cdot 10^{-5}$

where T is measured temperature of melt [K]; *EMV* is electromotive voltage [V].

There are measured values of oxygen activity in Table 2.

Chemical composition of cast iron for casting brake discs were monitored by Q4 TASMAN spectrometer. Determining of the chemical composition is given in Table 3. Castings ventilated brake disc were performed to bentonite moulds.

From a supposed chemical composition, there were calculated the degrees of

$$S_C = \frac{3.26}{4.23 - 0.3 \cdot (1.79 + 0.02)} = 0.88\% \quad (12)$$

TABLE 3. Chemical composition of lamellar cast iron.

Chemical composition, % wt.									
C	Si	Mn	Cr	Ni	Cu	Mo	P	S	C_E
3.26	1.79	0.75	0.09	0.02	0.25	–	0.02	0.09	3.64

and of

$$C_E = 4.25 - (1.79 + 0.02)/3 = 3.64. \quad (13)$$

3.3. Metallographic Evaluation of the Lamellar Cast Iron Structure

The metallographic evaluation was performed to assess and verify the preparation of the melt and the entire metallurgical process. According to the structure, in order to assess of the accuracy of quality of the cast iron, samples for metallographic evaluation of the structure casts were taken from the centre of the plates and were prepared by standard metallographic method (cut and polished).

Specimens were etched with 3% Nital (5% nitric acid by volume, dissolved in methanol) for 30 seconds. Specimen surfaces were then observed. Observation of the structure was carried out by light microscopy using Neophot-21 (Carl Zeiss Jena, Germany). The shape, size and distribution of the graphite were observed on samples non-etched in a state at a magnification of ×100 (see Fig. 3). Figure 4 presents a structure of matrix grey cast in the etched state. In Figure 5, the fractures surfaces of the disc are shown.

3.4. Measuring of the Hardness of Cast Iron Ventilated Brake Disc

Hardness measurements of individual ventilated brake disc were performed by using the Brinell hardness from Karl Weiss Jena. The identifier was steel ball with a diameter of 5 mm. The applied during 30 s load was 750 kp (*i.e.*, 7354 N; it is given a prescription for production). Hardness was measured at seven points on the upper surface of the casting (see Fig. 2) at the inlet and facing the flow commonly used

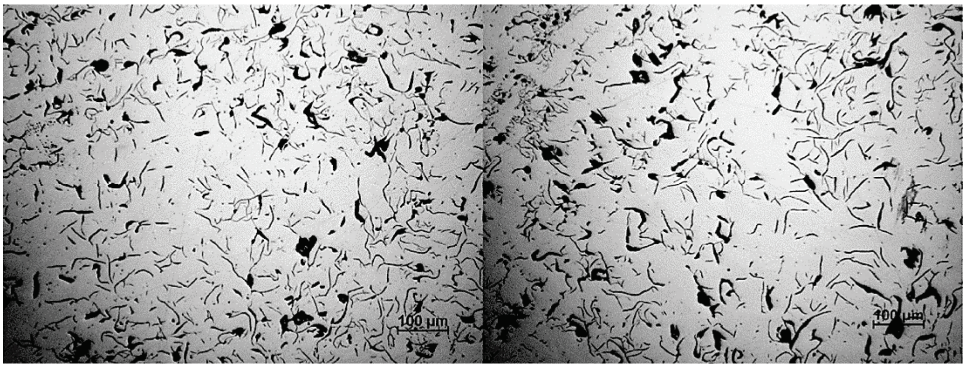

Fig. 3. Structure of graphite in cast iron of the ventilated brake disc (not etched).

Fig. 4. Structure of the ventilated brake disc from cast iron (etched—Nital 3%).

method. The final measured values are presented in Table 4.

The measured hardness values were statistically evaluated. It was determined the arithmetic average hardness x, standard deviation and coefficient of variation of hardness.

Arithmetic average hardness (x) was calculated as follows:

$$x = \frac{1}{n}\sum_{i=1}^{n} x_i, \tag{14}$$

where n is number of measurements, x_i is measured hardness value.

Standard deviation of hardness (s) is:

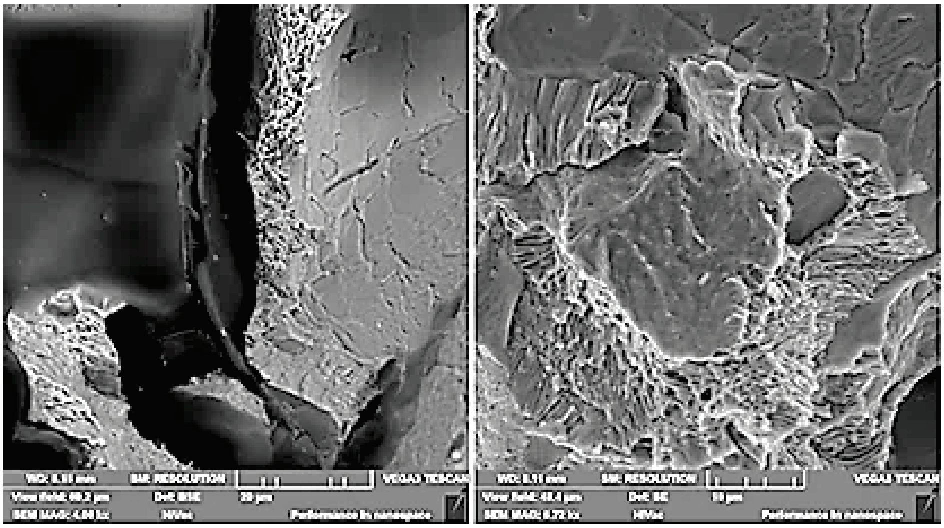

Fig. 5. The fracture surface of the ventilated brake disc.

TABLE 4. Measured values of the hardness (HB) of the ventilated brake discs.

Brake disc	Hardness (HB)							Statistical values		
								x (HB)	s (HB)	v [1]
1	229	229	230	229	229	231	231	229.71	1.55	0.0067
2	228	230	228	229	229	230	227	228.67	1.11	0.0049
3	229	229	231	230	230	229	229	229.50	0.86	0.0038
4	228	229	229	231	233	231	229	230.01	1.60	0.0069
5	228	232	231	230	229	235	229	230.57	2.19	0.0095
6	228	229	232	232	232	233	226	230.29	2.43	0.1060
7	230	231	229	234	232	230	233	231.29	1.67	0.0072
Average values								230.01	1.63	0.0200

$$s = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(x_i - x)^2}. \quad (15)$$

Variation coefficient of hardness (v) is:

$$v = s/x. \quad (16)$$

3.5. Evaluation of Quality of Cast Iron Ventilated Brake Disc Using Non-Destructive Methods

The evaluation of cast iron quality is realized by using non-destructive methods of retentive magnetism and ultrasonic thickness gauge. These methods are used in measuring devices called in Czech as TELIT, DOMENA-B3, or DOMENA-gHr [10, 11].

The device DOMENA-gHr (see Fig. 6) works on the principle of retentive magnetism and can be used to determine the structure of cast iron matrix with use a value of wall thickness of the casting (L_U) determined on the basis of ultrasonic measurements. Caliper or other measuring instrument is determined by the actual wall thickness of the casting (L). It was measured after 7 castings of cast iron ventilated brake disc, and tensile strength and Young's modulus are determined too. Measured values are shown in Table 5. Calculated values are found using Eqs. (17)–(19).

The value of the modulus of cast iron elasticity corresponding to the reference point on the cast was calculated based on the relationship:

$$E_0 = \left(\frac{L}{L_U}437.8\right)^2 \text{ [MPa]}. \quad (17)$$

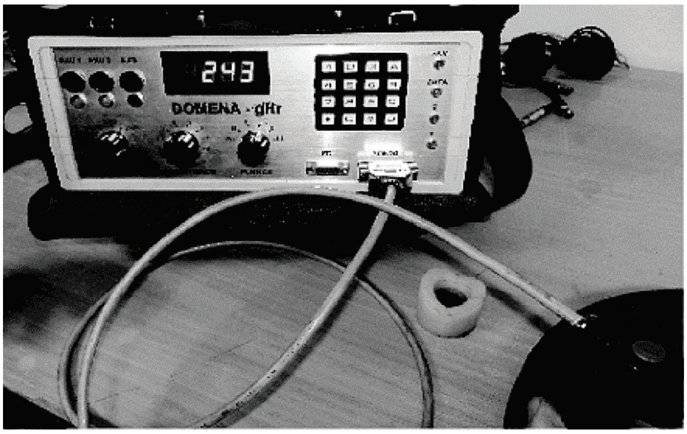

Fig. 6. The device DOMENA-gHr (made in Czech Republic) for cast iron analysis [10].

Equation for the value of Rm [MPa] of cast iron is as follows:

$$Rm = 7.2\left(\frac{L}{L_U}\right)^{2.28} HB^{0.75}. \quad (18)$$

Determination of hardness by measurement of the residual magnetic field is performed by formula:

$$HB = 0.6M + 100, \quad (19)$$

where M is a measured value of the residual magnetic field (using device DOMENA-gHr).

TABLE 5. Measured and calculated by Eqs. (17)–(19) values of mechanical properties of cast iron.

Broke disc	L, mm	E_0, MPa	Rm, MPa	M, A·m^{-1}	HB
1	8.50	136500	325	243	232
2	8.35	133600	316	246	232
3	8.34	133300	315	256	232
4	8.34	134700	321	246	232
5	8.45	136800	326	241	233
6	8.40	132600	313	237	233
7	8.37	138300	337	251	234
Average value		135115	321.9	210.4	232.6

4. CONCLUSION

In terms of physical metallurgy, the melt metal is a complex solution, which may contain for the production of high-quality grey iron a number of unsuitable elements. These elements can adversely affect the properties of the produced iron for the automotive industry, *e.g.*, brake discs and brake drums must meet the required physical and mechanical properties. From industrial practice of disks car manufacturers, it is evident that it is possible to divide the brake disc in terms of material into three quality groups (determined by E, hardness HB 5/750 and partly by Rm, which expresses the tensile strength in the standard conditions—plate thickness of 15 mm): discs that comply with EN 200 and EN GJS, GJS 250. Some manufacturers of discs must follow special rules of consumers, *e.g.*, BMG. Sometimes security necessary properties discs are connected with alloying wheel around. In companies for the production of cars, there are standards for brake discs and drums. The VW Company includes brake discs and drums from a materials perspective to the group GG 25 according to DIN 1691, *i.e.*, CSN EN GJL 250. The information in this document are the chemical composition required CEV and S_C-type structures are conceived but very broad and correspond to values for CSN EN GJL 200. According to the usual well-known relations, S_C value for CSN EN 250 should move correctly between 0.87 and 0.93. Similarly, it is necessary to modify the internal regulation ranges allowable C content (at 3.2 to 3.45%) and Si (at 1.6 to 2.3%). These proposed limits of critical elements can be internally adjusted by amount and type of alloying or inoculants used and the properties and hardness. There is also a critical ratio C/Si. In terms of rapid and non-destructive identification of quality, cast iron discs can use the device DOMENA (made in Czech Republic). It was found by comparing the measured values of hardness tester and set on the basis of the method of magnetic spots (device DOMENA) that differ by 2 to 5 HB.

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