Chapter

Evaluation of Metallurgical Quality of Cast Iron Using Quality Criteria

Peter Futas and Alena Pribulova

Abstract

The metallurgical quality of the produced cast iron is related to its chemical composition (mainly the content of C, Si, Mn, P, and S), or other monitored elements—alloying elements (Cr, Ni, Cu, ...), in some cases showing elements (Pb, Sn, As, Sb, ...). The chemical composition of cast iron is determined by the degree of saturation (Sc) or carbon equivalent (CE). Other factors influencing the quality of cast iron are the metallurgical conditions of production (melting and treatment) of cast iron and the rate of solidification in the mold. The mechanical properties of cast iron (Rm, HB, and E0) are closely related to its chemical composition. In addition to this common evaluation of cast iron, other quality criteria of gray cast iron are also used in practice. This is a comparison of the mechanical properties of the produced gray cast iron with the optimal values determined for the same degree of saturation (Sc). This chapter concerns assessments of the metallurgical quality of gray cast iron and the results of operational melting of synthetic gray cast iron with different charge compositions in the Slovak Foundry and its analysis.

Keywords: metallurgy, quality criteria, cast iron, properties, steel scrap

1. Introduction

Cast irons are alloys of iron, carbon, silicon, manganese, and other elements, while carbon is excluded in the form of graphite or is bound as carbide Fe_3C or carbide of another element. The carbon content exceeds the value of the maximum solubility of carbon in austenite, that is, C > 2.06% without the influence of other elements. Crystallizes according to the stable Fe–C or metastable Fe–Fe_3C diagram, or during solidification and cooling using both systems (**Figure 1**) [1].

Gray cast iron is called gray because of the gray color on the fracture surface. It contains 1.5–4.3% C and 0.3–5% Si plus Mn, S, and P. It is brittle with low tensile strength but has good foundry properties.

The structure of cast iron is characterized by randomly oriented graphite flakes (**Figure 2**) [2]. The more sharp-edged the graphite formations are, the greater the notch effect, which reduces the plasticity of cast iron and increases brittleness.

The structure of gray cast iron usually has three phases: ferrite, pearlite, or martensite. The carbon content in the metal matrix exceeds 1%. It contains graphite in the form of three-dimensional structures, which have the shape of flakes on the metallographic surface. Their distribution and shape largely influence the properties of the

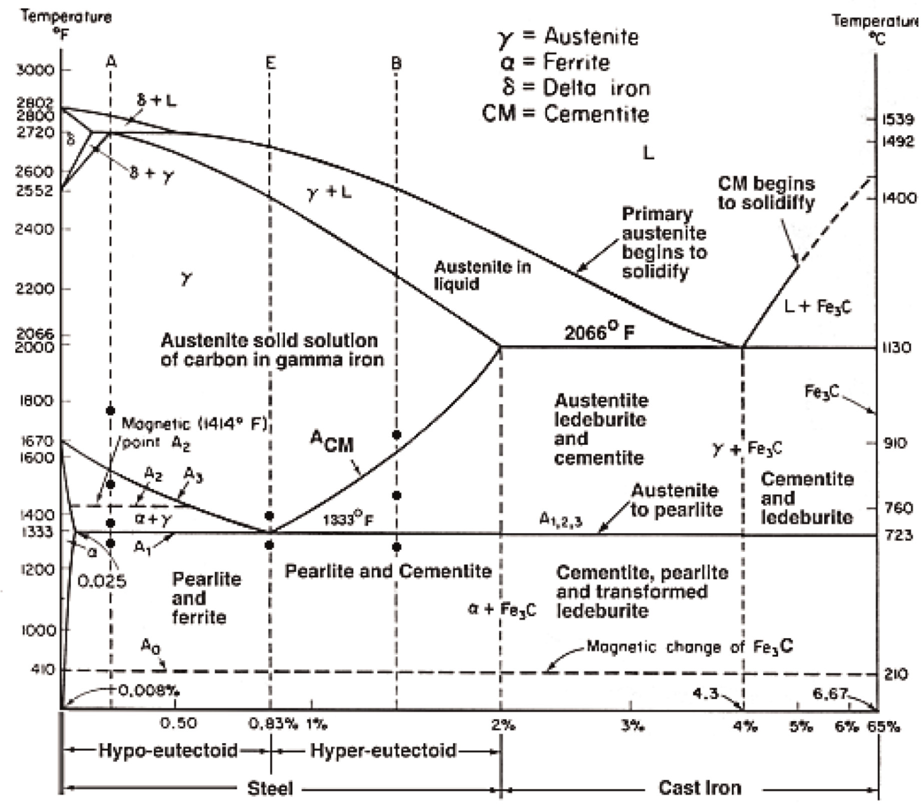
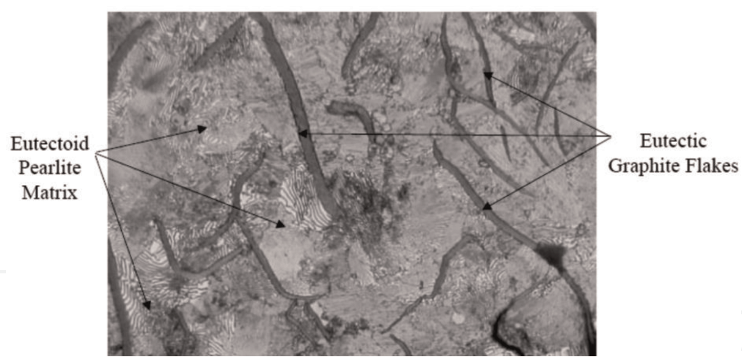


Figure 1.
Fe-Fe3C phase diagram [1].



Microstructure of Gray Cast Iron [2]

Figure 2.
Microstructure of gray cast iron [2].

material. The best gray cast irons have a metal matrix with graphite flakes of varying size and uniform distribution.

The chemical composition of gray cast iron should be chosen to ensure the following:

- Desired shape and distribution of graphite
- Carbide-free structure
- Required metal matrix

The structure of the metal matrix affects the properties as follows:

- Ferrite matrix—low strength
- Perlite matrix—higher strength
- Martensitic matrix—high strength and higher hardness when high-carbon cast irons are quenched.

Besides carbon, silicon is the most important element in cast iron. During solidification, it significantly supports graphitization, and during the transformation of austenite, it supports the formation of ferrite.

Gray cast iron is a widely used material in the automotive industry for engine blocks, brake discs, brake drums, and covers. It has good machinability with excellent wear resistance and excellent vibration damping. Thanks to its physical properties, it is preferred by designers and enables the production of castings with excellent specific properties, especially heat and fire resistant, abrasion resistant, and castings with special physical properties [3]. Its disadvantage is its fragility and relatively large dispersion of properties, especially mechanical ones, even with the same chemical composition. Solving this phenomenon requires excellent metallurgical and technological knowledge [4].

The worldwide trend of gray iron shares 54.4% (51,190,987 tons in 2021) [5].

2. Quality evaluation of gray iron

The quality of gray cast iron, usually expressed by values of mechanical properties (Rm, HB, and E_0), is closely related to its chemical composition (content of C, Si, Mn, P, and S) eventually other monitored elements—alloying elements (Cr, Ni, Cu, …), in some cases, pollutants (Pb, Sn, As, Sb, …) [6].

From a chemical point of view, gray cast iron is evaluated from the three main categories [7]:

1. *The main elements:* These are carbon, silicon, and iron. Gray cast irons typically contain 3.0–3.5% carbon, with silicon levels varying from 1.8 to 2.4%. Although increasing the carbon and silicon contents improves the graphitization potential and therefore decreases the chilling tendency, the strength is adversely affected. This is due to ferrite promotion and the coarsening of pearlite.

2. *The minor elements:* Phosphorus and the two related elements, manganese and sulfur. Phosphorus is found in all gray irons, and although rarely added intentionally, it does increase the fluidity of iron to some extent. Thus, most castings are produced with 0.02–0.10% P. Sulfur plays a significant role in the nucleation of graphite in gray iron, with optimum benefit at 0.05–0.12% sulfur levels. It is also important to note that sulfur levels need to be balanced with manganese to promote the formation of manganese sulfides. Typically, it can be as low as 0.1% for ferritic irons and as high as 1.2% for pearlitic irons because manganese is a strong pearlite promoter.

The optimum ratio between manganese and sulfur for a FeS-free structure and maximum amount of ferrite is [8]:

$$\%\text{Mn} = 1.7\text{x}(\%\text{S}) + 0.15$$

Other minor elements, such as aluminum, antimony, arsenic, bismuth, lead, magnesium, cerium, and calcium, can significantly alter both the graphite morphology and the microstructure of the matrix [9, 10].

3. *The trace elements:* Many other elements are utilized in limited amounts to affect the nature and properties of gray iron. Although some are not intentional, they do have a measurable effect on the gray cast iron. Some promote pearlite, such as tin, while others compact graphite and increase strength, such as nitrogen [11, 12].

The chemical composition is simply determined by the carbon equivalent (CE) or degree of saturation (Sc) [13].

2.1 Carbon equivalent

It takes the influence of the accompanying elements equal to the effect of the carbon into account and provides information on the composition relative to the eutectic composition in analogy to the degree of saturation, that is, it expresses the equivalent carbon content with respect to the iron-carbon binary system [6]:

$$CE = C + \frac{Si + P}{3} \tag{1}$$

In eutectic compositions, CE equals 4.3%; the following relationships exist between the degree of saturation and the carbon equivalent CE, mainly used in the Anglo-American countries [6]:

$$Sc = \frac{C}{4.23 - CE + C} \tag{2}$$

$$CE = 4.3 + C\left(1 - \frac{1}{Sc}\right) \tag{3}$$

In all formulas, C is to be replaced with the total carbon content.

2.2 Degree of saturation

It indicates the ratio between the total carbon content of the melt and the carbon content of the eutectic composition. According to Eq. (4), it is under consideration of the influence of accompanying elements on the shifting of the eutectic point [6]:

$$Sc = \frac{C}{4.26 - \frac{1}{3}(Si + P)} \tag{4}$$

If other accompanying elements in the iron or alloy components are also considered, this results in the following exact formula Eq. (5) [6]:

$$Sc = \frac{C}{4.26 - 0.31.Si - 0.27.P - 0.4.S - 0.074.Cu + 0.063.Cr + 0.02.Mn} \tag{5}$$

A degree of saturation Sc = 1.0 means that the iron corresponds exactly to the eutectic composition.

Degrees of saturation above 1.0 have hypereutectic cast iron and thus result in the structural formations of cast iron to be expected under consideration of the relevant wall thicknesses. In the chemical composition of flake graphite cast iron, carbon has the strongest influence on the strength.

The lower the carbon content and the degree of saturation, the greater the strength because less graphite and more primary dendrites are present in the structure. Manganese, phosphorous, and sulfur in the usual contents have only a minor influence on tensile strength. Inoculation treatment results in an increase in the number of eutectic cells and thus in greater strength. The so-called Sipp diagram (**Figure 3**) [14], illustrates the correlations with regard to the material structure and the Heller-Jungbluth diagram (**Figure 4**) [14], those with regard to the tensile strength.

The degree of saturation can also be used for the approximate calculation of the tensile strength of gray cast iron depending on the wall thickness. According to Eq. (6) [6]:

$$\text{Normal tensile strength Rm (MPa)} = 1000\text{–}800\ \text{Sc (for the standard 30 mm test bar)} \quad (6)$$

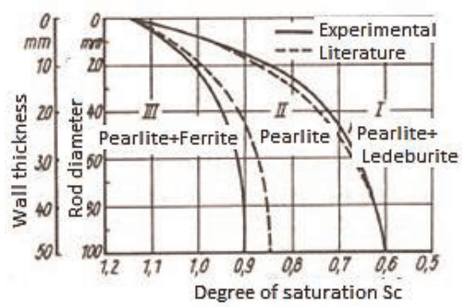


Figure 3.
Relation between the degree of saturation and the basic structure [14].

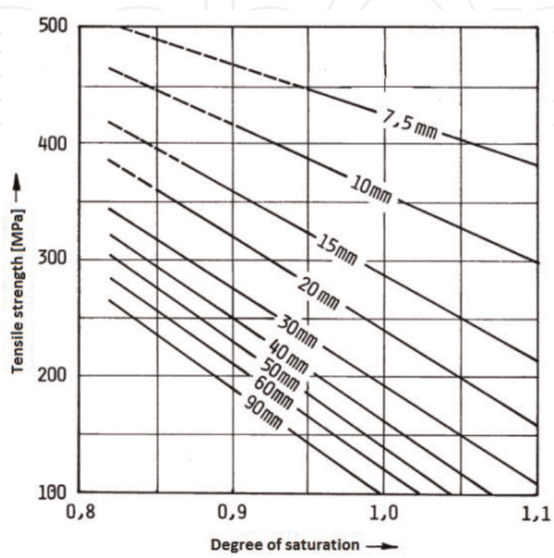


Figure 4.
Relation between the degree of saturation and the tensile strength of flake graphite cast iron [14].

The quotient of measured tensile strength and calculated normal tensile strength indicate the so-called degree of normality, an important quality parameter of the flake graphite cast iron.

There is a correlation between the degree of saturation and the carbon equivalent.

For most applications, a gray, pearlitic cast iron with a degree of saturation of approximately 0.85 to 0.95 for wall thicknesses of around 15 mm is preferred, with a carbon content of approximately 3.1 to 3.3% and a silicone content of 1.5 to 1.8%. As a general rule, the Si/C proportion for a given degree of saturation should be adjusted to a possibly high value.

They are used in quality criteria of gray iron in engineering practice, in addition to ordinary quality evaluation of cast iron, that is, determination of Rm and HB, eventually chemical composition or other required properties. This is a comparison of the mechanical properties of gray iron produced with optimal values determined for the same degree of saturation.

2.3 Regression equations for calculation of mechanical properties

Statistical methods (regression equations with multiple correlations) determine the quantitative relationship among the chemical compositions (basic, if necessary, accompanied by other observed items), or the degree of saturation or carbon equivalent CE and strength and toughness of gray cast iron, in some cases modulus of elasticity E_0.

The most used equations to calculate the mechanical properties of pearlitic gray iron from its chemical composition are [6, 14]:

$$Rm = 786.5–150\%C–47\%Si + 45\%Mn + 219\%S;\ \text{variation } s = 25\text{ MPa} \quad (7)$$

$$HB = 444–71.8\%C–13.9\%Si + 21\%Mn + 170\%S;\ \text{variation } s = 12.46 \quad (8)$$

$$E_0 = 313.175–449.014\%C - 14082\%Si;\ \text{variation } s = 6760\text{ MPa} \quad (9)$$

The most appropriate procedure is to calculate the regression equation for its own foundry (i.e., for the specific conditions).

2.4 The quality criteria

The degree of maturity of cast iron RG specifies the level of quality of gray iron production compared with the optimal, determined by calculation, value of Sc, respectively, by correlation Eq. (6):

$$RG = \frac{Rm_{measured}}{Rm_{calculated}} \bullet 100\% \quad (10)$$

where $Rm_{calculated}$ = 1000–800 Sc

It also determines *the relative hardness RH* [6]*:*

$$RH = \frac{HB_{measured}}{HB_{calculated}} \bullet 100\% \quad (11)$$

where $HB_{calculated}$ = 100 + 0.44 $Rm_{measured}$.

A value above 100% means a high quality of gray iron.

The quality number GZ or quality factor is obtained by dividing the RG/RH or by Rm/HB—measured values. Qualitative gray iron has high strength at low hardness.

3. Evaluation of quality of gray iron in a particular foundry

In the operational, conditions of foundry in Slovakia have analyzed 122 melts of gray iron EN-GJL-250 with different charges. The steel scrap rate was 77.82% and the return material was 22.18%. In the foundry, also one melt with a 100% rate of the steel scrap in the charge was realized (synthetic gray iron).

These melts were realized in two low-frequency induction furnaces “Siemens” with the following parameters:

- the nominal content of the furnace: 6 tons
- melting furnace power: 5350 kg/h
- nominal frequency: 50 Hz

The cast iron was by the bar gauge treated FeSi75. The temperature of the superheated melt was between 1420 and 1440°C.

Next samples were a cast from the melts:

- samples for chemical analysis
- test bars with a diameter of 30 mm (tensile strength—Rm, Brinell Hardness HB)

The samples for metallographic analysis were taken from the test bars and prepared in a standard manner.

The hardness was measured with the durometer HPO 3000 (terms: 10/3000/10), that is, the diameter of the ball was 10 mm, strength duration was 3000 N, and period of load was 10 sec.

Tensile strength was measured on test bars (Ø30 mm) on the universal crackle machine ZWICK.

The statistical results of the chemical composition and measured mechanical properties are documented in **Table 1**.

The stress results of gray iron (EN1561) show small dispersion of Rm (260–285 MPa), the average value of Rm = 274 MPa, which confirms the uniformity of production. The decrease of Rm by an increase of Sc is slight (**Figure 5**).

For the melt with 100% steel scrap, the charge hardness that was greater at approximately 45% (HB 293) was recorded. But on the other side, the gray iron had lower tensile strength (Rm = 226 MPa) against average values from other melts.

More than half of the melts were produced with a lower Sc than the specified EN (Sc min. 0.87). The average value of Sc = 0.850 is below this value too. It is possible to expect the opposite result in the production of synthetic gray iron (100% steel scrap).

The average value HB = 201 is optimal for this brand of gray iron even though the dispersion of the values HB (183–225) is relatively high in a whole range of the chemical composition (Sc = 0.798–0.934) (**Figure 6**).

On the base of multiple regressions [15], dependence equations of tensile strength Rm and Brinell Hardness HB on C, Mn, Si, P, S, and Cr were calculated.

Furnace charge average n = 122	C	Mn	Si	S	P	Cr	Sc	CE	Rm [MPa]	HB
	(%)									
Return material	3.211	0.826	1.575	0.0624	0.136	0.116	0.850	3.664	274	201
22.18% steel	0.074	0.0711	0.096	0.0437	0.05	0.034	0.1114	0.4781	6.0415	11.23
scrap 77.82%	3.0	0.66	1.19	0.024	0.06	0.04	0.798	3.456	260	183
steel	3.4	0.98	1.81	0.094	0.27	0.18	0.934	3.988	285	225
scrap 100%	3.28	0.78	1.79	0.063	0.18	0.09	0.901	—	226	293

NOTE: the first line—*arithmetic average,* the second line—*standard deviation,* the third line—*the lowest value of the file,* the fourth line—*the highest value of the file, and n—number of melts.*

Table 1.
The statistical results of the chemical composition and the mechanical properties.

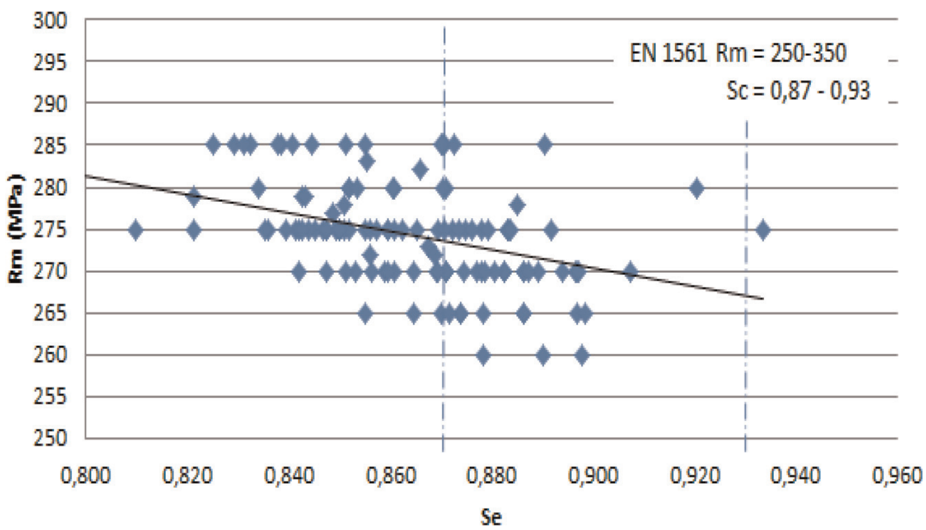


Figure 5.
Influence of the degree of saturation on the tensile strength Rm.

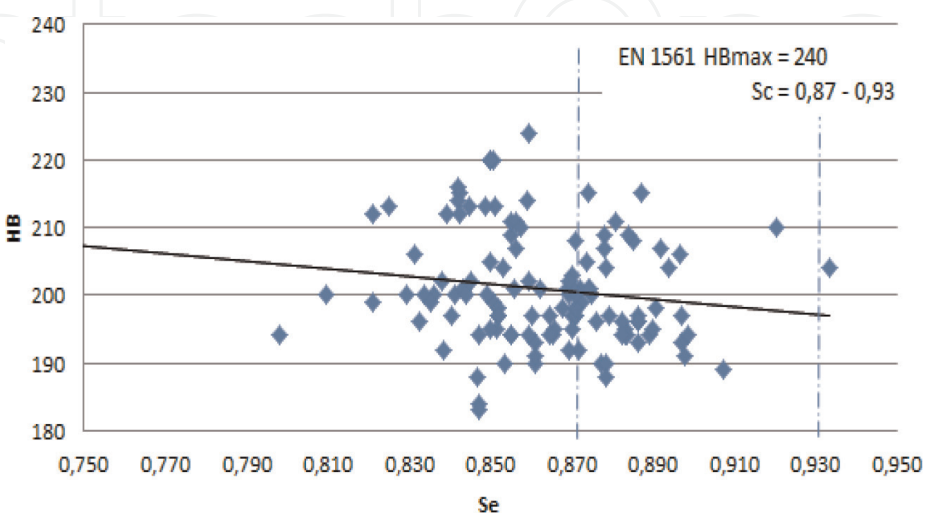


Figure 6.
Influence of the degree of saturation on the Brinell hardness HB.

Tensile strength (MPa):

$$Rm = 340.53–17.15\%C + 19.7\%Mn–10.68\%Si–34.23\%P + 10.37\%S–57.76\%Cr \quad (12)$$

correlation coefficient 0.5849.
deviation s = 51.922.
significance level α = 0.05.

Brinell Hardness HB:

$$HB = 284.21–19.3\%C–31.17\%Mn + 6.49\%Si–19.98\%P–11.66\%S–31.08\%Cr \quad (13)$$

correlation coefficient 0.3852.
deviation s = 69.118.
significance level α = 0.05.

Regression dependence of the chemical composition on tensile strength Rm and Brinell Hardness HB identically show the most significant effect of content C, Mn, and Cr with literature data [16, 17].

The influence of sulfur is interesting, which increases the strength and reduces the hardness in evaluated melts.

The content of phosphorus, normally not evaluated, is significant in evaluated melts—it reduces both tensile strength Rm as well as Brinell Hardness HB.

Besides the standard evaluation of quality for cast iron by tensile strength and hardness eventually by chemical composition, the quality criteria were also evaluated (**Table 2**). It was the criteria that quantitatively represent the effect of particular production conditions on reached cast iron properties in comparison with the optimal statistically valid conditions. Really quality cast iron should show the highest degree of maturity RG and the lowest relative hardness RH.

The quality criteria for cast iron produced from 100% steel scrap rate are shown in **Table 3**. From the quality criteria (**Tables 2** and **3**), it can be stated that produced cast irons show a lower degree of maturity, which means they have lower strength than corresponds with their chemical composition. On the other side, synthetic cast iron shows a high relative hardness that in the final result decreases its quality number.

From the identified quality criteria, it can be concluded that produced gray irons show the average values of quality, while the degree of maturity RG is higher (114.5%) and the relative hardness RH is slightly lower. It is the result of the composition of the charge (without pig iron) as well as the result of low overheating of cast iron (1420–1440°C), but it is recommended to overheat it above 1480°C (for economic reasons). Despite these results of the quality criteria, it can be concluded that produced gray iron complies with EN.

The evaluated quality criteria	
The degree of maturity of cast iron RG (%)	114.5
The relative hardness RH	0.91
The quality factor m	1.363
The quality number GZ	125.8

Table 2.
The quality criteria.

The evaluated quality criteria	
The degree of maturity of cast iron RG (%)	82.57
The relative hardness RH	1.469
The quality factor m	0.771
The quality number GZ	56.21

Table 3.
The quality criteria of synthetic gray iron.

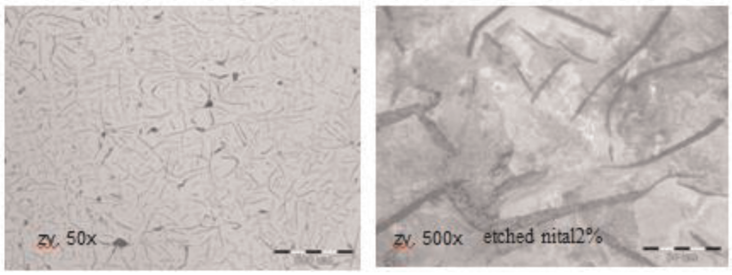


Figure 7.
Typical microstructure of gray iron of standard melts.

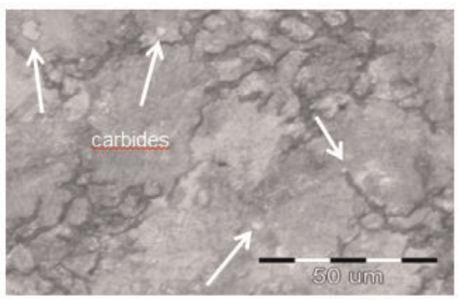


Figure 8.
Microstructure of synthetic gray iron, etched 2% Nital, 500x.

The microstructure of all melts was pearlitic with a 92–96% portion of pearlite (**Figure 7**). Cementite in the structure of melts was not observed.

In synthetic gray iron (100% steel scrap), there was full pearlitic microstructure and there were detected carbides (**Figure 8**). Attendant of these carbides was the cause of higher hardness in this gray iron.

Besides the significant influence of the chemical composition of gray iron, which is necessary to evaluate more complex, that is, including desirable and undesirable additives—chemical elements and impurities, the quality of cast iron is closely related to the metallurgy of its production. These include the following:

- quality of raw materials for a batch,
- type of furnace,
- smelting process (metallurgical processes),
- out of furnace treatment of liquid metal, and

- casting temperature.

The highest quality and the most widely used batch material for the smelting of iron is pig iron. Its quality is highly variable; it is linked up with the manufacturer, that is, the conditions of the blast furnace production. Most often, it is contaminated with trace elements and different gas content (N, H, and O), or their compounds (impurities). It is necessary to measure the content of Ti (up to 0.15%), Ca (up to 0.025%), Al (up to 0.004%), and Ni, Cr, Cu, V at its choice.

Besides the common types of foundry and steel industry pig irons, there are now also produced synthetic and semi-synthetic types that are characterized by their specific properties. It is important to check the quality of the new brand (new manufacturer) and to use one type of pig iron for a long time.

Another, particularly cost-effective batch material is steel scrap, and its quality is very diverse. Its use in the greater proportion is currently at smelting in electric furnaces (EIF and also EAF)—up to 100% share in the production of synthetic iron. The properties of such cast iron are significantly different from the properties of cast iron produced from the cupola furnace (max. 30% of steel), respectively; cast iron is produced with a higher proportion of pig iron.

It is necessary to know the quality (purity) of other batch materials, especially scrap iron, reversible material, and various impure iron-containing materials and their impact on the final quality of cast iron. Affordable material is cast iron turnings, without negative effect on the quality of the cast iron, especially the roughing of own castings.

Metallurgical processes and therefore the quality of the resulting cast iron are related to the type of furnace. The most important metallurgical parameters of smelting are temperature of the overheated metal, its standing time after melting-down, as well as the possibility of some metallurgical processes during smelting (desulfurization, dephosphorization, reduction of gases, etc.). The most extensive metallurgical treatment options are in the electric arc furnace. However, the procedure is more energy demanding.

Today, there are extensive options available (procedures and equipment) for desirable out-of-furnace treatment of liquid cast iron, which not only increases its quality, but also the cost of its production.

The general rule is to keep the lowest temperature of the casting, which is most closely connected with the wall thickness and weight of the cast and with the liquidus temperature of casting cast iron. Low casting temperature positively affects crystallization (formation of macro- and microstructure) and uniformity of characteristics of the cross section of the walls and various parts of the cast iron and, especially, it reduces the tendency to form micro- and macroshrinkages as well as heat stress during solidification.

4. Conclusions

The production of high-quality cast iron according to EN-GJL-250 (EN 1561) with a lower level of $Sc < 1$ is possible mainly in the production of thick-walled castings with a guaranteed higher required hardness. Many factors affect the quality of cast iron. Their significance is still being investigated, often with quite unexpected results (sulfur content in gray iron). For an easy assessment of the metallurgical quality evaluated by mechanical properties, statistical methods are used, especially multiple correlation and comparison with the achieved optimal parameters.

Quantitative relationships between chemical composition and tensile strength Rm and hardness HB were determined using statistical methods (multiple correlation regression equations). The following conclusions follow from the results of operational smelting in the foundry:

- C, Mn, and Cr have the most significant influence on tensile strength Rm and hardness HB.
- the quality of EN-GJL 250 (EN 1561) cast iron was mainly ensured by the reduction of Sc, which is related to the production of heavy, thick-walled castings with a guaranteed higher hardness on the walls of the casting (microalloying Cr).
- with a decrease in Sc, almost all foundry-technological properties of gray cast iron deteriorate, especially run-in and tendency to shrinkage and formation of chill-out, respectively, hard places in the corners and thin walls of the casting, which impairs their machinability. This effect was recorded in the foundry.

From the quality criteria, it can be concluded that the produced cast iron shows a lower level of RG; that is, they have lower strength than corresponds to their chemical composition. Synthetic cast iron (100% steel scrap), on the other hand, exhibits high relative hardness, which ultimately lowers its quality number (GZ 56.21).

It is a result of low overheating of cast iron (1420–1440°C); it is recommended to overheat up to 1480°C.

The desired final quality of gray cast iron is closely related to the customer's requirements, as well as to the financial costs of securing it. The difference in costs for the production of up to 100% synthetic LLG is the most current (up to €200/t).

Acknowledgements

This work was supported by the Scientific Grant Agency of The Ministry of Education of the Slovak republic No. KEGA 018TUKE-4/2022, KEGA 004TUKE-4/2023, VEGA 1/0002/22, VEGA 1/0265/21, and APVV-19-0559.

Author details

Peter Futas* and Alena Pribulova
Technical University of Kosice, Kosice, Slovakia

*Address all correspondence to: peter.futas@tuke.sk

References

[1] Pollack H. Fe-Fe3C Phase Diagram. Materials Science and Metallurgy. 4th ed. Hoboken, New Jersey, United States: Prentice-Hall; 1998

[2] Ihm M. Introduction to Gray Cast Iron: Brake Rotor Metallurgy. Livonia, Michigan, United States: TRW Automotive; 2013

[3] Collini L, Nicoletto G, Konečná R. Microstructure and mechanical properties of pearlitic gray cast iron. Materials Science and Engineering. 2008;**488**:529-539

[4] Kotus M, Andrassyova Z, Cico P, Fries J, Hrabe P. Analysis of wear resistant weld materials in laboratory conditions. Research in Agricultural Engineering. 2011;**57**:74-78

[5] Modern Casting. 2021. Available from: http://cdn.coverstand.com/55001/687958/3ba370da37f7b6c13efcbf97a5335c779891062b.4.pdf

[6] Futáš P, Pribulova A, Pokusova M, Junakova A. Liatiny—Vlastnosti, výroba, použitie, Košice. 2020

[7] Singh R. Cast iron metallurgy. Materials Performance, Materials Selection & Design. 2009;**9**:58-61

[8] Pereira A, Boehsa L, Guesserb W. The influence of sulfur on the machinability of gray cast iron. Journal of Materials Processing Technology. 2006;**179**:165-171

[9] Kumar B, Singha A. Effect on the mechanical properties of gray cast iron with variation copper and molybdenum as alloying elements. International Journal of Engineering Research & Technology. 2014;**3**:81-84

[10] Baron AA, Palatkina LV. Choice of the optimum criterion for estimating the strength of gray cast iron using the primary structure parameters. Russian Metallurgy. 2021;**5**:1555-6255

[11] Sujana W, Widi KA, Rahardjo T, Prihatmi T, N. The ability of nitrogen atomic absorption in the formation of iron nitride on flake structure and nodule in cast iron. In: Annual Conference on Science and Technology (ANCOSET 2020) IOP Publishing Journal of Physics: Conference Series 1869. Malang, Indonesia: 2021

[12] Abhijit Ramesh Patil PN. Gore: Study of factors affecting tensile strength of gray cast iron. Journal of University of Shanghai for Science and Technology. 2021;**23**(11):759-768

[13] Lian XT, Zhu JN, Dong H, Wang YM, Liu JD. Effects of micro-alloying elements on microstructure, element distribution and mechanical properties in gray irons. International Journal of Metalcasting. 2020;**14**(4): 1025-1032

[14] Döpp R. Beitrag zur Entwicklung der Eisengussdiagramme. Giesserei Rundschau. 2013;**60**:328-334

[15] Mertler C, Vannatta R, LaVenia K. Advanced and Multivariate Statistical Methods. Routledge, New York: 2021. DOI: 10.4324/9781003047223

[16] Futas P, Pribulova A, Fedorko G, Molnar V. Influence of steel scrap in the charge on the properties of gray iron. ISIJ International. 2017;**57**(2):374-379

[17] Baron AA, Palatkina LV. Relation between the hardness and the strength of gray cast iron with allowance for the structural parameters. Russian Metallurgy (Metally). 2017;**11**:984-988