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Assessment of the Quality of Ductile Cast Iron EN-GJS-500-7 Through the Influence of its Chemical Composition on the Grain Composition of Spheroidal Graphite

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Abstract

Quantitative evaluation of the microstructure obtained in a product is nowadays commonly required both in R&D activities and during routine quality control of materials and components.
This paper presents an assessment of the quality of ductile cast iron, based on investigations of the effect of chemical composition on the distribution of ductile graphite precipitates in low-alloy cast iron EN-GJS-500-7. The size of graphite precipitates was expressed in terms of equivalent cross-sectional diameter, which made it possible to describe the distribution of graphite precipitates with a function simulating the log-normal distribution of graphite. The resulting *U*, *W* and *Z* parameters were statistically analysed, including the effect of chemical composition on graphite distribution. In the studied cast iron, the components that increase the *U* parameter are silicon, manganese and phosphorus, thus favourably affecting the total graphite number. In contrast, the constituents that decrease the *U* parameter are carbon, chromium and aluminium.

Keywords: Ductile cast iron; Chemical composition; Graphite precipitates; Stereological parameters

1. Introduction

The microstructure of any engineering material is far from being in a geometrically ordered state. In turn, the spatial structure of the alloy is a testimony to the effectiveness of any technological treatment, such as modification or spheroidization carried out on the liquid alloy. Thus, the metallographic spatial structure is a determinant of the properties of such a construction material [1]. Ductile cast iron is characterised by a very wide range of mechanical properties depending on the number and size of graphite separations and the type of matrix [2]. Hence its widespread use in the construction of typical parts and devices where increased strength is required, which depends on the matrix, i.e. the chemical composition. It is possible to obtain tensile strength R_m = 400÷1200 MPa [3-4], it is also characterised by plastic properties amounting to A_5 = 2÷25% [5]. The continuous progress in science and technology has resulted in the introduction of a large number of ductile cast irons with very diverse compositions and properties, used mainly in areas such as the automotive industry, as well as in the shipbuilding and engineering industries, especially in the case of structural components of machining machines, or flanges of pump and valve parts. A number of scientific researches, as well as the expectations of users, are evidence of the search for the best quality ductile cast irons. Factors that influence the properties of cast iron include the chemical composition of the matrix and the size, distribution, volume fraction and morphology of the individual components of the microstructure. The quality of cast iron depends on the form in which the carbon is released, which can be in the form of spheroidal graphite or in the form of fine plate graphite. The microstructure of unalloyed cast iron typically consists of M3C carbides and perlite, with the carbide phases imparting hardness and causing an increase in UTS (R_m). Among the broader family of cast irons, ductile iron is the most extensively studied material, as indicated by the existence of an extensive literature in this area, e.g.: [2,6-9].

The increasing demand for cast products is usually accompanied by increasing demands on material properties. The quantitative description of the microstructure obtained in the product is of great importance [9]. In the case of ductile cast iron, the decisive factor is the quality (shape, number and size) of graphite precipitates and the type of matrix. If the same melting and crystallization conditions are maintained in the tests (the structure of cast iron is a function of the physico-chemical state of the liquid metal and the process of crystallization and solidification), conclusions about the physico-chemical state of the liquid metal can be drawn on the basis of the structure of the obtained cast [10]. This paper attempts to describe the grain composition of graphite in ductile iron. The description of the graphite distribution was made using a function simulating a log-normal distribution. In the work carried out, the parameters of the distribution function of the spheroidal graphite precipitates of the cast iron under study were determined, and these parameters were then used as a data set to search for the relationship between the grain composition of graphite and the chemical composition, which was the aim of this work.

In order to unambiguously determine the simulation function, only three parameters informing about the average size, number and size variation of the graphite analysed are sufficient. This will allow defining all stereological parameters of the investigated cast iron as an isometric structure [1].

2. Testing methodology

In the course of the conducted tests, 52 industrial melts of ductile cast iron of the EN-GJS-500-7 grade with the TYPE II (Y2) test shape according to PN-EN1563 were made from which samples were taken for testing. Cast iron was melted in a crucible induction furnace with a capacity of 8 tones and a frequency of 50Hz, which was cast in bentonite moulds according to the technology and monitoring of finished cast iron specified in the ITACAXTM system [11]. The feedstock used was 80% Sorelmetal synthetic pig iron and 20% W10 grade steel scrap according to the PN-85/H-15000 standard.

Table 1 illustrates the basic statistical parameters of the distribution of alloying elements content of the examined EN-GJS-500-7 ductile cast iron.

Table 1.
Statistical distribution of alloying elements of cast iron EN-GJS-500-7

Alloying elements	Minimum	Maximum	Mean value	Standard deviation
	Content of alloying elements in weight %			
C	3,48	3,68	3,5800	0,05855
S	0,001	0,003	0,0018	0,00097
Si	2,76	2,95	2,8300	0,06694
Mn	0,24	0,28	0,2460	0,01200
Cr	0,06	0,07	0,6300	0,00458
Ni	0,023	0,027	0,0247	0,0010049
Mo	0,003	0,004	0,0039	0,00030
V	0,024	0,028	0,0249	0,00137
Ti	0,011	0,011	0,011	0
Cu	0,16	0,308	0,2126	0,05473
Al.	0,015	0,26	0,0186	0,00382
P	0,046	0,05	0,0477	0,00110
Co	0,016	0,019	0,0167	0,00118
As	0,004	0,004	0,0040	0

In order to prepare the smelter samples for graphite precipitates, samples were taken from the smelter samples with different cross-sections, from which the smelter samples were made using the traditional method under industrial conditions according to PN-EN ISO 17639:2013-12. For etching, 5% Nital reagent was selected, which among others reveals the ferrite grain boundaries, alloy structure, etches grain boundaries and is used to reveal segregation of graphite precipitates.

A quantitative description of the graphite precipitates was made using an optical microscope NICON ECLIPSE MA200, equipped with a graphic programme for metallographic evaluation NIS-Elements. The measurements were carried out on a monitor screen consisting of 2592 x 1944 points. For the x40 lens used the calibration factor was 0.11 μm/pt, while the measurement area was 200 000 μm^2. Measurements were made on 5 measuring fields for each sample, and for each graphite precipitate and measuring field, measurements were made of the basic stereological parameters, i.e. the real surface area of the spheroidal graphite, the real diameter of its cross-section, the radius of its theoretical surface area, and the total surface area of the graphite precipitate.

3. Functional description of the distribution of graphite precipitates

The description of the size distribution of the alloy microparticles was made on the basis of quantitative metallography on the widely accepted Bockstiegel theorem, according to which the most appropriate exponent of the particle size is the equivalent diameter of a sphere *D* or the equivalent diameter *d* of a cross-section [1]. Based on this theorem, the graphite precipitate sizes obtained from the measurements were converted into equivalent section diameters. In a subsequent step, the distributions of graphite precipitates reflected by the equivalent diameters were visualised using a function describing a log-normal distribution. A direct expression for the number of graphite precipitates as a function of the (real) particle cross-sectional diameter d was calculated using the following formula [1].

$$N_A\,(d) = U \frac{Zexp[Z(W-lnd)]}{\{1+\exp[Z(W-lnd)]\}^2} \tag{1}$$

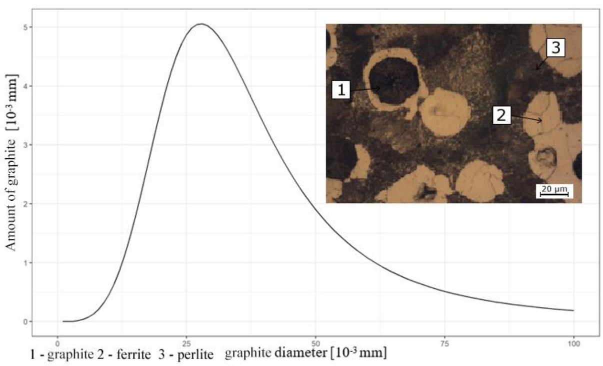
Where:
d - diameter of graphite particle [10^{-3}mm]
U - index of the total number of graphite particle [10^{-3} mm/mm^2]
W - logarithmic graphite particle size diameter [10^{-3} mm]
Z - graphite particle size variation [10^{-3} mm].

The values of parameters U, W and Z of the function simulating the graphite particle size distribution were determined from the measurements made in a numerical manner. Table 2 presents the descriptive characteristics for the calculated parameters U, W and Z of the simulating function.

Table 2.
Descriptive characteristics of the parameters of the simulation function

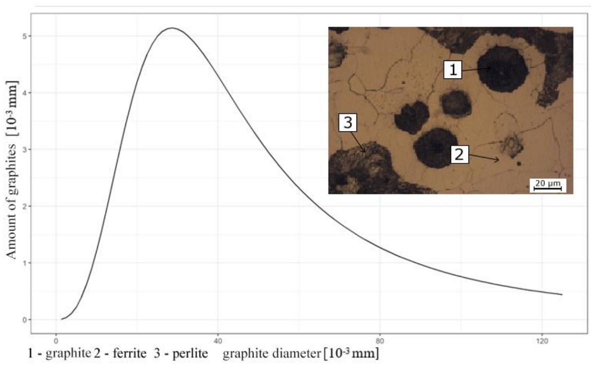
Variable	Parameter	Total
U	Mean (SD)	4,83 (2,64)
	Median (IQR)	3,8 (2,91 - 7,38)
	Range	1,62 - 9
W	Mean (SD)	3,49 (0,25)
	Median (IQR)	3,46 (3,35 - 3,7)
	Range	3 - 3,8
Z	Mean (SD)	10,31 (7)
	Median (IQR)	10,21 (4,09 - 15,67)
	Range	2,19 - 21,05

Figures 1÷4 illustrate the distributions of the number of graphite particles in the selected samples in relation to the values of the graphite particle diameter, as well as the corresponding image of the graphite particles on the deposit prepared for testing.



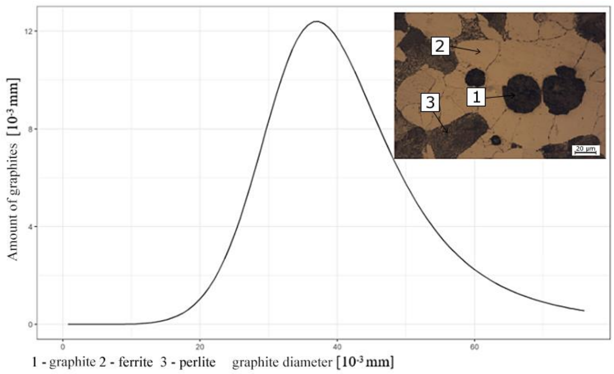
	Chemical composition [%] mas.						
Melting point No.	C	Si	Mn	Cu	Cr	P	V
	3.38	2.86	0.24	0.161	0.006	0.049	0.024
	Mo	Ni	Al	Co	Ti	As	S
	0.004	0,025	0,026	0.016	0.011	0.004	0.003

Fig. 1. Distribution of graphite particles amounts - melt I: U = 5.55, W = 3.32, Z = 3.65



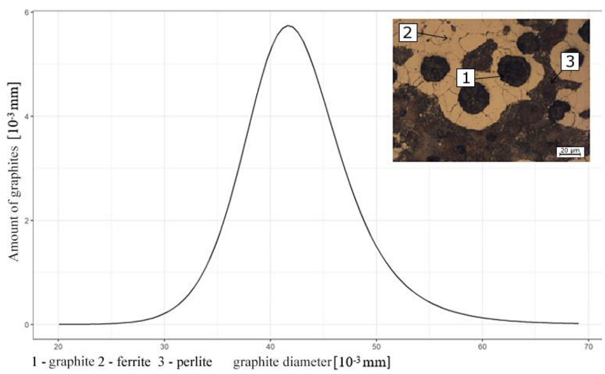
	Chemical composition [%] mas.						
Melting point No. II	C	Si	Mn	Cu	Cr	P	V
	3.57	2.95	0.24	0.163	0.06	0.050	0.024
	Mo	Ni	Al	Co	Ti	As	S
	0.004	0,024	0,025	0.016	0.011	0.004	0.001

Fig. 2. Distribution of graphite particles amounts - melt II: U= 7.99, W= 3.35, Z= 2,58



	Chemical composition [%] mas.						
Melting point No. V	C	Si	Mn	Cu	Cr	P	V
	3.52	2.80	0.25	0.16	0.06	0.047	0.024
	Mo	Ni	Al	Co	Ti	As	S
	0.003	0,024	0,017	0.016	0.011	0.004	0.002

Fig. 3. Distribution of graphite particles amounts - melt V: U= 7.99, W= 3.61, Z= 6.21



Melting point No. IX	Chemical composition [%] mas.						
	C	Si	Mn	Cu	Cr	P	V
	3.63	2.87	0.24	0.246	0.07	0.048	0.027
	Mo	Ni	Al	Co	Ti	As	S
	0.004	0,027	0,016	0.019	0.011	0.004	0.001

Fig. 4. Distribution of graphite particles amounts - melt IX: *U*=1.61, *W*= 3.73, *Z*= 14.22

4. Regression models for the dependence of parameters of the function parameters on the alloying elements of the tested cast iron

From the observation of the graphs presented in Figures 1÷4 of the distributions of the number of spheroidal graphite particle precipitates in individual specimens relative to the graphite diameter value, it can be seen that the chemical composition of EN-GJS-500-7 cast iron plays an important role in shaping the grain composition of spheroidal graphite. In order to determine the influence of individual alloying elements on graphite precipitation, both the *U*, *W* and *Z* parameters and the chemical composition of the cast iron were statistically analysed. The stepwise regression method was applied, which allows for easy elimination of irrelevant factors, and in the presented linear regression equation models, it was determined which alloying elements and in what direction influence the *U*, *W* and *Z* parameters. Statistical calculations yielded the following relationships:

- for the *U* index - total number of graphite precipitates [10^{-3} mm /mm^2]:

U = -14.483 - 26.31C + 8.687Si + 91.969Mn - 428.999Cr - 698.479Ni + 2637.483P - 822.542Al

with statistical parameters: mean value = 4.83, median = 3.8, range = 1.62 - 9, significance level = 0.05, coefficient of determination = 99.07%

- for the index *W* - logarithmic mean graphite precipitate size [10-3 mm]:

W = -4.6 + 5.361C -7.109Si - 1171.515Mo + 4.962Cu +106.815Cr -154.516Ni +140.355P + 156.982Al

with statistical parameters: mean value = 3.49 median = 3.46, range = 3 - 3.8, significance level = 0.05, coefficient of determination = 66.79%

- for *Z* index - variation in graphite precipitate size [1/10-3 mm]:

Z= -175.561+81.001C -70.688Si +280.253Mn -58.495Cu +1589.815Cr -491.472Ni -1499.302P + 1237.219Al

with statistical parameters: mean value = 10.31, median = 10.21, range = 2.19 - 21.05, significance level = 0.05, coefficient of determination = 99.62%.

5. Conclusion

The use of a simulation function to describe spheroidal graphite precipitates allows all stereological relationships in quantitative metallography to be analysed using only three parameters. The statistical relationships included above allow the stereological parameters of the graphite particles to be analysed in an accessible way, depending on the chemical composition of the cast iron. In the cast iron studied, the components that favourably influence the total number of graphite precipitates are silicon, manganese and phosphorus, as they increase the *U* parameter, while at the same time they do not contribute to changes in the logarithmic mean graphite particle size (*W* parameter) or in the variation of graphite particle size (*Z* parameter). In contrast, the components that adversely affect the fineness of graphite particles are carbon, chromium and aluminium, causing a reduction in the *U* parameter (their summed number). It is worth noting that these components, like silicon, manganese and phosphorus, also do not contribute to changes in the W parameter (the logarithmic mean size of graphite particles).

The statistical equations presented relate to the assessment of the quality of the cast iron under test on the basis of three parameters, and the collected data set allows for the development of other statistical relationships. The research results obtained as a result of these calculations will be of utilitarian significance, and should find application in industrial conditions in order to increase the effectiveness of cast iron quality assessment, in accordance with the objective of the research conducted.

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