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Control of Selected Properties of „Vari-Morph" (VM) Cast Iron by Means of the Graphite form Influence, Described by the Mean Shape Indicator

J. Zych *, M. Myszka, N. Kaźnica
AGH University of Science and Technology, Faculty of Foundry Engineering,
Department of Moulding Materials, Mould Technology and Cast Non-Ferrous Metals,
Al. Mickiewicza 30, 30-059 Kraków, Poland
* Corresponding author: e-mail: jzych@agh.edu.pl

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Abstract

The graphite form in cast iron is the structure parameter deciding on its all physical and mechanical properties. Three basic forms of graphite: flake, vermicular (compact) and nodular (spheroidal) are singled out in standard cast iron grades, without a heat treatment. Standards of individual grades of cast iron the most often allow only the homogeneous graphite form, sometimes with addition of 5÷10% of the other form.

The interesting and - in the authors opinion - future-oriented material can constitute cast iron in which various forms of graphite are present, e.g. in comparative amounts: spherical and vermicular cast irons. Cast iron within which graphite occurs in two or three forms was named „Vari-Morph" (VM) cast iron, i.e. the one in which spherical and vermicular or vermicular and flake graphite occur in a wide range of proportions. The results of investigations of these new cast iron grades and their properties are presented in the hereby paper.

Keywords: VM cast iron, Graphite shape indicator, Heat fatigue, Properties: ρ, λ, R_m, A_5

1. Introduction

Cast iron is a material, which mechanical, physical, technological and functional properties are formed by graphite (its shape, distribution and size) and by a metallic matrix, which the most often is ferrite, pearlite or their mixture. Simultaneously this is the subject of many studies [1-7]. Generally, three grades of cast iron are produced: grey cast iron (flake graphite), vermicular cast iron (compact graphite) and spheroidal cast iron (nodular graphite). It is assumed, that in the casting structure of each cast iron grade occurs graphite, homogenous in respect of its shape, and the homogeneity degree is not smaller than 90 - 95%. Grey and spheroidal cast irons dominate in the world industrial practice.

The technological standards do not predict producing cast irons with a mixed graphite. Cast iron with a mixed graphite forms, with controlled fractions of individual shapes, which proposed name is VM cast iron ('Vari - Morph'), can become an interesting material for castings of special requirements. This VM cast iron is characterized by physical and mechanical properties, which cannot be achieved when graphite is homogeneous in respect of its shape. VM cast iron is between cast iron with flake (F) graphite and vermicular (V) graphite and in between vermicular (V) and spheroidal (S) graphite.

Cast irons with F+V graphite will be characterized by a good thermal conductivity and better plasticity and strength than grey cast iron. Especially interesting is cast iron with a mixed form: graphite (S) + graphite (V). Such cast iron will have high strength and plasticity, tightness, relatively good ability of damping vibrations and good thermal conductivity. It was shown in papers [8-12], that such cast iron is characterized also by a high heat fatigue resistance higher than vermicular cast iron.

2. Investigation methodology

The results of investigations of the selected group of physical (λ – thermal conductivity, ρ – density, C_L – wave speed), mechanical (R_m and A_5) and functional (N – thermal fatigue resistance) properties of „VM" cast iron is presented in the hereby paper. The ultrasound technique was applied for assessing the graphite compactness degree.

Influence of the graphite form on the tested cast iron properties were determined and described as functions of the graphite shape factor (f_K), which was changing its values within the range from 0.25 to 0.90. To be able to determine the shape indicator value, on the basis of the microstructure image, the own calculation methodology was developed. This methodology applies the computer program for the analysis of calculations based on the program data. The authors methodology of determining the averaged value of the shape indicator of graphite precipitates is described below.

3. Results of own investigations

The group of cast iron grades, which chemical composition oscillated near the eutectic value, was subjected to investigations (C = 3.3÷3.6%, Si = 2.6÷2.95%, Mn < 0.1; P < 0.02%; S < 0.01%; Mg = 0.005÷0.030%). The graphite shape classification was based on the indicator shape of graphite ξ, which was defined by formula 1:

$$\xi = \frac{A_i}{P_i^2} \qquad (1)$$

where: A_i , P_i - surface (m^2) and diameter (m), respectively, of a single precipitate, i - number of graphite precipitates.

Indicator ξ takes the following values: 0÷0.03 ($\xi < 0.03$) for flake graphite, 0.035 ÷ 0.065 for vermicular graphite, 0.065 ÷ 0.08 ($\xi > 0.065$) for nodular graphite.

The spheroidisation process realised with the controlled amount of magnesium (Mg) introduced to cast iron was performed in two ways: with using the elastic rod (method PE – Fig. 1) or with the application of the Tundish type ladle (Fig. 2). In case of spheroidisation with the PE usage a velocity of the rod, being introduced into liquid metal, is also controlled. The ladle with the tightly closed cover (Tundish ladle) on which bottom the mortar FeSiMg9 is introduced and covered by chips of spheroidal cast iron, is shown in Fig. 2.

Fig. 1. Laboratory set-up for cast iron spheroidisation by means of the PE method

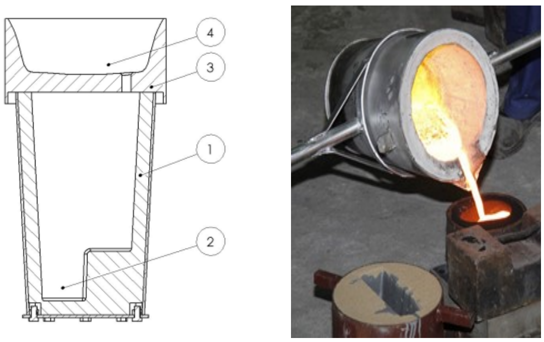
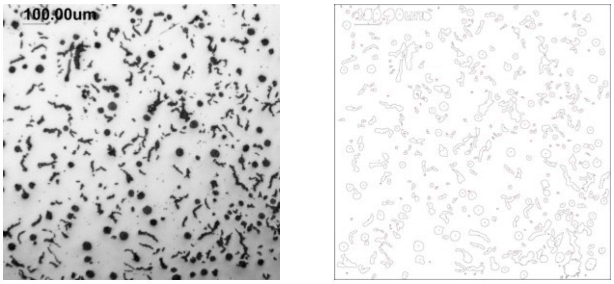


Fig. 2. Tundish type ladle with the cover: 1 – ladle, 2- pocket for FeSiMg, 3- cover; 4 – pouring basin

Tests of the spheroidisation processes indicated that in case of the PE method the magnesium yield was approximately 40%, while in case of the Tundish ladle – more than 65%.

Determination of the graphite shape indicator

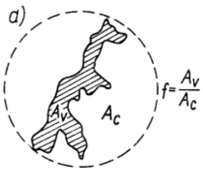
Microscopic images were subjected to the stereological analysis by means of the program Image J for pictures analysing. The microstructure image in digital recording and the image processed by the Image J program are shown in figure 3, as an example.



a) Microstructure image b) Image processed by the Image J

Fig. 3. Microstructures of cast iron (VM) - with a mixed graphite form

Each graphite precipitate is recorded by the program by means of the graphite shape indicator included in equation 2.



$$f = \frac{A_V}{A_c} \qquad (2)$$

Fig. 4. Scheme of shapes of graphite precipitates cross-sections [12]

The procedure of determining the mean shape indicator was performed in subsequent steps in which the written below values were determined:

- ➢ number of graphite precipitates per mm^2 (with omitting precipitates being on the picture edges and the ones which surface is smaller than 80 μm^2), Fig. 5,
- ➢ surface percentage fraction of graphite,
- ➢ surface of each precipitate,
- ➢ diameter of the circle on the precipitate corresponding to its highest dimension.

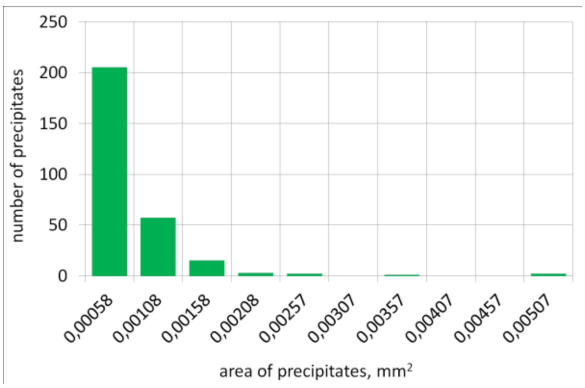


Fig. 5. Number of graphite precipitates in individual surface classes

The graphite shape indicator f was determined for each precipitate, acc. to [14], in accordance with equation (2), where :
A_v — surface of the graphite precipitate [mm^2],
A_c — area of the circle of a diameter equal the highest particle dimension [mm^2].

The shape indicator f_K theoretically changes from 0.0 to 1.0, while under real conditions from app. 0.20 to 0.95.
It was assumed that the shape indicator of graphite is changing within ranges:

- ➢ 0.00–0.34 for flake graphite,
- ➢ 0.35–0.64 for vermicular graphite,
- ➢ 0.65–1.00 for spheroidal graphite.

In the next step the number of precipitates of the shape indicator f being in individual ranges, was calculated and their percentage fraction in relation to all precipitates, was determined. For each range the separate mean indicator f was determined. They constituted the bases for calculating the main shape indicator f_K, based on the weighted mean.

Individual results of graphite shape analyses obtained in the assumed calculation procedure, are listed in Table 1.

Table 1.
Analysis of the shape indicator

Graphite shape	Number of precipitates	% fraction of the range	Mean „f" of the range	Indicator f_K
Flake	59	21.6	0.26	0.59
Vermicular	98	35.9	0.48	
Spheroidal	116	42.5	0.85	

It was indicated, on the basis of the performed calculations that the mean indicator of the graphite shape f_K = 0.59, which classifies precipitates as vermicular graphite. Simultaneously the spheroidal degree is N = 42.5%. Fractions of individual kinds of graphite shapes are shown in Fig. 6. One of the results of the complex assessment of graphite precipitates is placing them within ranges of the shape indicator f, shown in figure 7. In the analysed case of VM cast iron precipitates, which shape indicator f_K is within the range about 0.30-0.40, corresponding to the lower range of the vermicular graphite, are dominating. However, the largest number of precipitates in a single range of the shape indicator f is characteristic for 0.91-0.99. The shape indicator for each cast iron from successive melts was determined in the same way.

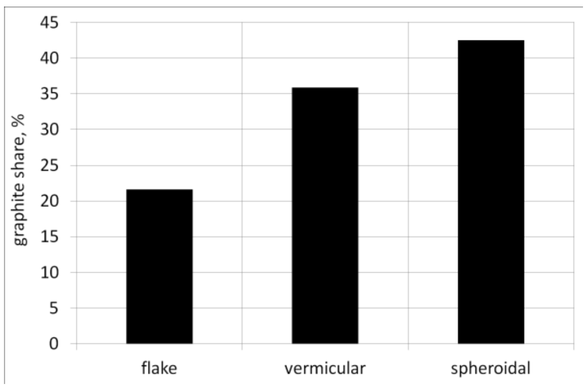


Fig. 6. Fractions of individual graphite kinds

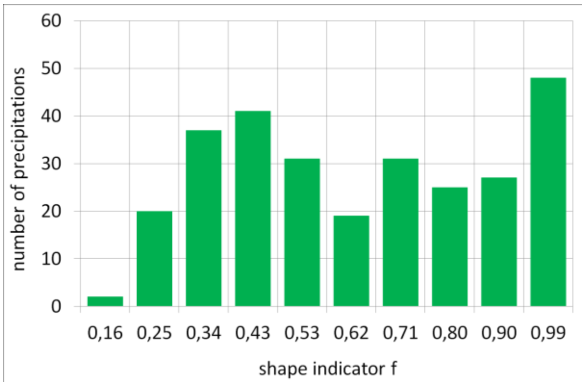


Fig. 7. Number of graphite precipitates as a function of the shape indicator

Results of own investigations

Applying the described melting methodology the material for tests was prepared in forms of test coupons Y type, from which samples for individual tests were made. The following physical properties were assessed: specific density, ability to propagate longitudinal waves and thermal conductivity of VM cast iron. These properties of „Vari Morph" (VM) cast iron depend on the graphite form f_K, which allows to determine dependencies: $\rho = f(f_K)$; $C_L = f(f_K)$ and $\lambda = f(f_K)$. The limited Mn content in cast iron allowed to obtain purely ferrite cast iron or ferrite with a small (to app. 15%) pearlite fraction. In this way the influence of the metallic matrix kind on the tested properties of cast iron, was eliminated.

Specific density (ρ) of VM cast iron was determined by the immersion method with using the tensometric weight adapted to these measurements. The procedure of the sample density measuring was the standard one.

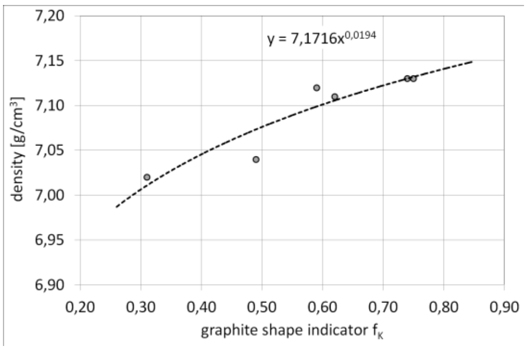


Fig. 8. Influence of the graphite form (indicator f_K) on the VM cast iron density

The results of investigations of the influence of the graphite precipitates shape on the density of VM cast iron are presented in figure 8. It was found in metallographic tests that the graphite amount, measured as the surface taken on the polished section, was similar in all tests. This was due to maintaining the stabilised chemical composition of cast iron. It can be noticed that the transfer from flake via compact (vermicular) to the spheroidal form of graphite, causes the density increase by approximately 0.15 g/cm^3. The so-called compactness of material increases, which influences its certain properties such as: strength, tightness, plasticity.

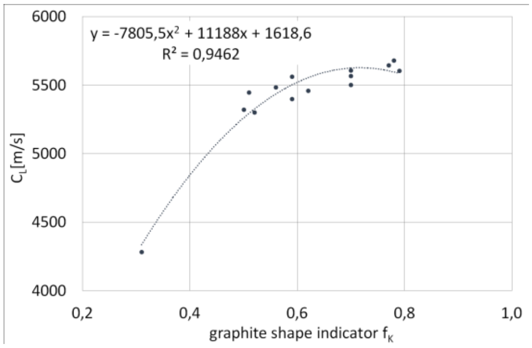


Fig. 9. Dependence of the mean shape indicator f_K and the ultrasound wave speed C_L

The ultrasound wave speed in cast iron depends on the graphite form and changes within a wide range [16-18]. This is confirmed by the results of investigations presented in figure 9. In investigations we are striving to the development of the empirical dependence $f = (C_L)$ for the whole variability range of the shape indicator. If such dependence is characterised by a high correlation coefficient (high certainty), the ultrasound technique will be used for the non-destructive assessment of the graphite shape indicator in ready castings. The results of tests, performed on a relatively not numerous group, indicate a good correlation between these two values.

In the future, VM cast iron is supposed to be the material, which structure - related to graphite precipitates shapes - will be 'adjusted' to the destination of the product and the character of its operation under real conditions. One of the features, which will be controlled is the thermal conductivity of cast iron. Investigations of the samples group obtained in successive melts were carried out on the prototyped research set-up, shown in figure 10. The thermal conductivity was determined under conditions of a stable heat flow in cylindrical samples of diameter ø20 mm and length 80 mm. The conductivity was determined within the temperature range T = 25 ÷ 500°C. The obtained results are presented in figure 11.

Fig. 10. Research set-up for testing the thermal conductivity of materials, including foundry metals and alloys

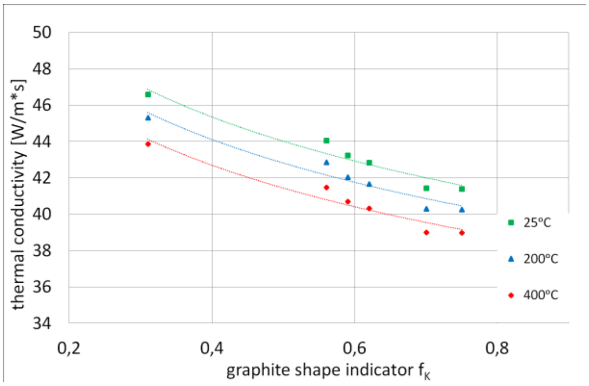


Fig. 11. Dependence between the graphite shape indicator and thermal conductivity of ferrite cast iron

It is generally known that the change of the graphite form from flake ($f_K \approx 0.25$) to spheroidal ($f_K > 0.75$) leads to decreasing of the thermal conductivity. The quantitative dependence, in which the graphite shape is described by the mean value of indicator f_K, is determined in the hereby paper.

The functional property of cast iron, which depends on the graphite form, is the heat fatigue resistance. The heat fatigue resistance tests were performed by means of the L. F. Coffin method, in which cylindrical samples are cyclically heated by resistance method. The results obtained for VM cast iron are presented in figure 12. Increasing the graphite shape indicator f_K value, increasing the compactness degree of graphite precipitates, favours increasing the heat fatigue resistance. However it should be noticed, that under real operational conditions of cyclically heated structure elements, the structures made of cast iron with more compact graphite (higher f_K indicator) will be heated to higher temperatures, due to their low conductivity (Fig. 11).

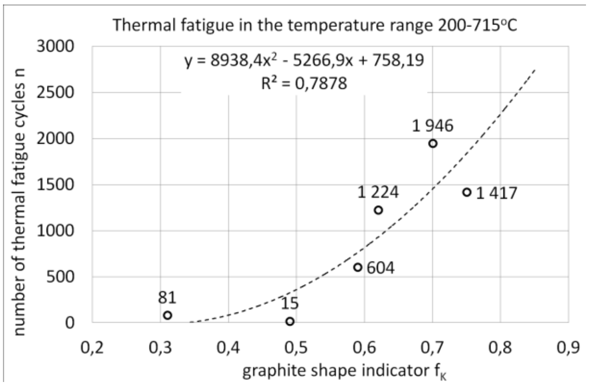


Fig. 12. Influence of the graphite shape indicator on heat fatigue resistance of VM cast iron

One of the most important mechanical properties, which are changing and a sort of 'following' the value of the graphite shape indicator, are tensile strength (R_m) and plasticity (A_5). At analysing the influence of the graphite precipitate shape on R_m and A_5 values the influence of the metallic matrix should be eliminated. Thus, tests should be performed on samples of the same matrices. The result obtained for ferrite cast iron are presented in figure 13. Although investigations are in their initial phase, it is possible to determine already numerical dependences between the shape indicator f_K and strength R_m of VM cast iron. By changing the graphite form within the range 0.30 ÷ 0.80 the increase of the cast iron strength from approximately 100 MPa to more than 500 MPa is achieved.

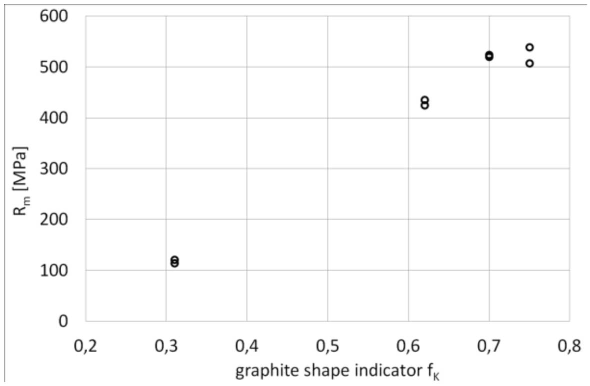


Fig. 13. Dependence between the graphite shape indicator and tensile strength R_m of VM cast iron of the ferrite matrix

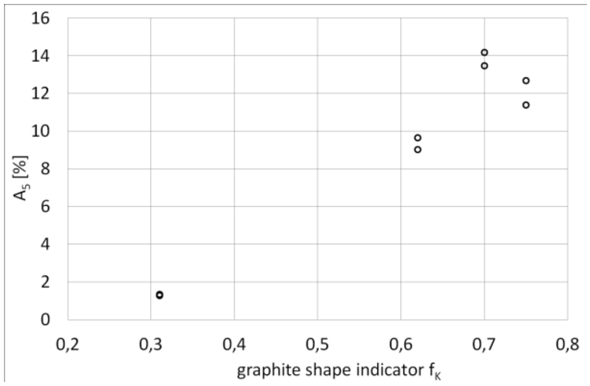


Fig. 14. Dependence between the graphite shape indicator and plasticity A_5 of VM cast iron of the ferrite matrix

Similarly strong influence of the graphite shape indicator is observed at tests of cast iron elongations and A_5 determining. The results are shown in figure 14. The indicator shape f_K change within the range 0.30 ÷ 0.80 causes the elongation increase of VM cast iron from app. 1.5 % to app. 14%. The direction of changes is known, thus tests concerns the determination of empirical dependencies, which will take the form of mathematical dependencies.

4. Conclusions

Investigations performed in this study allowed to determine empirically dependencies existing between the graphite shape indicator and the selected property, feature or functional property of VM cast iron. These are dependencies of:

- physical properties (specific density, thermal conductivity, ultrasound wave speed): $\lambda = f(f_K)$; $C_L = f(f_K)$; $\rho = f(f_K)$,

- mechanical properties (strength (R_m; $R_{0,2}$, A_5)): Rm = f(f_K); $R_{0,2}$ = f(f_K), A_5 = f(f_K),
- functional properties (heat fatigue resistance) N_{cycles}= f(f_K).

The computer aided methodology of determining the shape indicator was developed, with using the Image J program. This is a new method especially suitable in quantitative determinations of this indicator of cast iron grades having different graphite forms. This method is based on the concept of calculating the mean weighted value of the shape indicator and all visible separation on the microstructure are included in the calculation, regardless of their size and shape.

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