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Correlation between shape factor and mechanical properties of graphitic cast irons

Alan Vaško [1], Milan Vaško [2]

[1] University of Žilina, Faculty of Mechanical Engineering, Department of Materials Engineering, Univerzitná 8215/1, 010 26 Žilina, Slovakia, phone: +421–41–513 2605, e-mail: alan.vasko@fstroj.uniza.sk
[2] University of Žilina, Faculty of Mechanical Engineering, Department of Applied Mechanics, Univerzitná 8215/1, 010 26 Žilina, Slovakia, phone: +421–41–513 2981, e-mail: milan.vasko@fstroj.uniza.sk

Abstract The evaluation of shape factor (circularity) is a subject of interest in many fields of applications such as medicine and industrial processes. The shape factor plays an important role in materials science as a way to understand the relationship between microstructure and mechanical properties of technical materials. The paper deals with measurement of shape factor of graphitic particles with the aim to understand the influence of microstructure (especially shape of graphite) on mechanical properties of graphitic cast irons.

Key words – shape factor, cast iron, graphite, microstructure, mechanical properties

1. Introduction

Cast iron can be defined as an alloy of iron, carbon and other elements, where content of carbon is higher than maximal solubility of carbon in austenite. Graphitic cast irons contain carbon in the form of graphitic particles of different shape which directly influence their mechanical properties. Therefore, graphitic cast irons are commonly classified according to the shape of graphite in lamellar cast iron, vermicular cast iron and nodular cast iron (SKOČOVSKÝ P. 2005).

Lamellar cast iron (also known as gray cast iron) has graphite in the shape of a three-dimensional flake; in two dimensions the graphite flakes appear as fine lines (lamellas). Although the tensile strength of lamellar cast iron is relatively low and it is very brittle, it has high compressive strength coupled with excellent damping capacity. The main factor favoring the wide use of lamellar cast iron is its low cost.

Nodular cast iron (also known as ductile cast iron or spheroidal cast iron) is a type of graphitic cast iron, where the graphite occurs in the form of nodules. The formation of nodules is achieved by the addition of nodulizing elements (modificators), most commonly magnesium. Nodular cast iron has high tensile strength and high elongation. It can be produced in such a way as to enable a wide range of properties through control of the microstructure. The properties of nodular cast iron are not only dependent on the size, number and arrangement of graphitic nodules, but also on the basic matrix consisting of ferrite and pearlite. Higher ratio of pearlite increases tensile strength and hardness, higher ratio of ferrite increases toughness and elongation.

Vermicular cast iron (also known as compacted cast iron) has graphite in the shape of worms; the graphitic particles are shorter and thicker than lamellar graphite, with rounded edges. Vermicular graphite is a transitional form between lamellar and nodular graphite. It occurs when the cast iron is deliberately modified by insufficient amount of modificator. Vermicular cast iron falls between lamellar cast iron and nodular cast iron not only by its microstructure but also by its mechanical properties. Similar to nodular cast iron, these properties are markedly dependent on the ferrite-to-pearlite ratio in the metal matrix.

The comparison of mechanical properties of graphitic cast irons is given in Fig. 1 (SKOČOVSKÝ P. 2007).

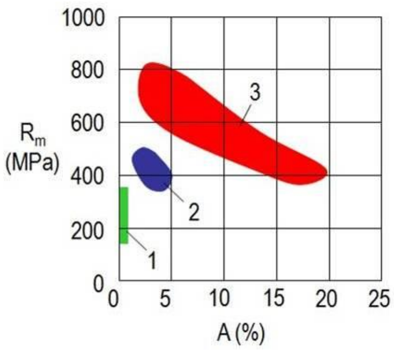


Fig. 1. Comparison of mechanical properties of graphitic cast irons; 1 – lamellar cast iron, 2 – vermicular cast iron, 3 – nodular cast iron

Source: SKOČOVSKÝ P. 2007

2. Experimental material and methods

The mechanical properties of graphitic cast irons are dependent especially on the shape of graphite. The size and uniformity of distribution of graphitic particles also influence properties, but to a lesser degree than shape of graphite. Therefore, the paper is concentrated on the evaluation of shape factor (circularity) of graphite.

Three specimens of graphitic cast irons with different shape of graphite (lamellar, vermicular and nodular) were used for experiments.

The static tensile test was made according to STN EN ISO 6892-1 by means of the testing equipment ZDM 30 with a loading range F = 0 to 50 kN. The impact bending test was made according to STN EN ISO 148-1 by means of the Charpy hammer PSW 300 with a nominal energy of 300 J (VAŠKO A. 2014, BORKOWSKI S. 2009).

The metallographic analysis of the specimens was made by the light metallographic microscope Neophot 32. The microstructure of specimens was evaluated according to STN EN ISO 945 (STN 42 0461). The automatic image analysis (using NIS Elements software) was used for evaluation of the shape of graphitic particles by a shape factor (circularity) (VAŠKO A. 2010, KONEČNÁ R. 2014., KUŚMIERCZAK S. 2014.).

Circularity plays an important role in materials engineering as a way to understand the mechanical properties of cast irons. The evaluation of the shape of graphite by means of different shape factors (Tab. 1) has been published in scientific papers (GOMES O.F.M. 2005, HERRERA-NAVARRO A.M. 2013, LI J. 2000, SKOČOVSKÝ P. 2007, SKOČOVSKÝ P. 1994.).

Table 1. Shape factors

Name	Definition
Circular shape factor	$CSF = \frac{4\pi A}{P^2}$ (1)
Roundness	$Round = \frac{4A}{\pi \cdot F_{max}^2}$ (2)
Modified CSF	$CSFm = \frac{4 \cdot A}{P \cdot F_{max}}$ (3)
Grum CSF	$CSFg = \frac{16 \cdot A^2}{\pi \cdot P \cdot F_{max}^3}$ (4)
Aspect ratio	$AR = \frac{F_{min}}{F_{max}}$ (5)
Modification ratio	$MR = \frac{W}{F_{max}}$ (6)
Branching factor	$BF = \frac{W}{F_{min}}$ (7)
Convexity	$Conv = \frac{P_c}{P}$ (8)
Solidity	$Sol = \frac{A}{A_c}$ (9)
Note: A – surface area, A_c – convex area, P – perimeter, P_c – convex perimeter, F_{min} – minimum feret, F_{max} – maximum feret, W – largest inscribed circle diameter	

Source: GOMES O.F.M. 2005

The most widely used measurement of circularity in current literature is the shape factor based on area and perimeter computations given by the formula (1):

$$S = \frac{4\pi A}{P^2}, \qquad (1)$$

where A is an area and P is a perimeter. It ranges within [0,1], where 1 is scored only by a perfect circle; all other shapes are characterized by a value smaller than 1.

Intervals of values of the shape factor for typical shapes of graphite are following:

– for lamellar graphite (I) ► $S < 0,3$;
– for vermicular graphite (III) ► $S = 0,3 – 0,6$;
– for imperfectly nodular graphite (V) ► $S = 0,6 – 0,9$;
– for regular nodular graphite (VI) ► $S = 0,9 – 1$.

3. Experimental results and discussion

Results of the evaluation of microstructure of the specimens according to STN EN ISO 945 (STN 42 0461) are presented in Tab. 2. From microstructural point of view, the first specimen (GJL) is a pearlite-ferritic lamellar cast iron, the second specimen (GJV) is a ferrite-pearlitic vermicular cast iron and the third specimen (GJS) is a ferrite-pearlitic nodular cast iron.

Table 2. Microstructure of the specimens

Specimen	Microstructure
GJL	IA4 – Fe8
GJV	80%III + 20%V6 – Fe80
GJS	90%VI6 + 10%V6 – Fe80

Source: own study

Results of the mechanical tests (that are tensile strength R_m, elongation A and absorbed energy K) are presented in Tab. 3.

The mechanical properties of the specimens of graphitic cast irons are dependent on microstructure, especially on the shape of graphite. The specimen of lamellar cast iron has the lowest tensile strength as well as the lowest elongation and absorbed energy; it is very brittle material. It is caused by sharp edges of the lamellar graphite which create stress concentration within the metal matrix. On the other hand, the specimen of nodular cast iron has the highest tensile strength as well as the highest elongation and absorbed energy. Rounded shape of the nodular graphite causes lesser stress concentration in comparison with lamellar graphite. The mechanical properties of the specimen of vermicular cast iron are between lamellar cast iron and nodular cast iron.

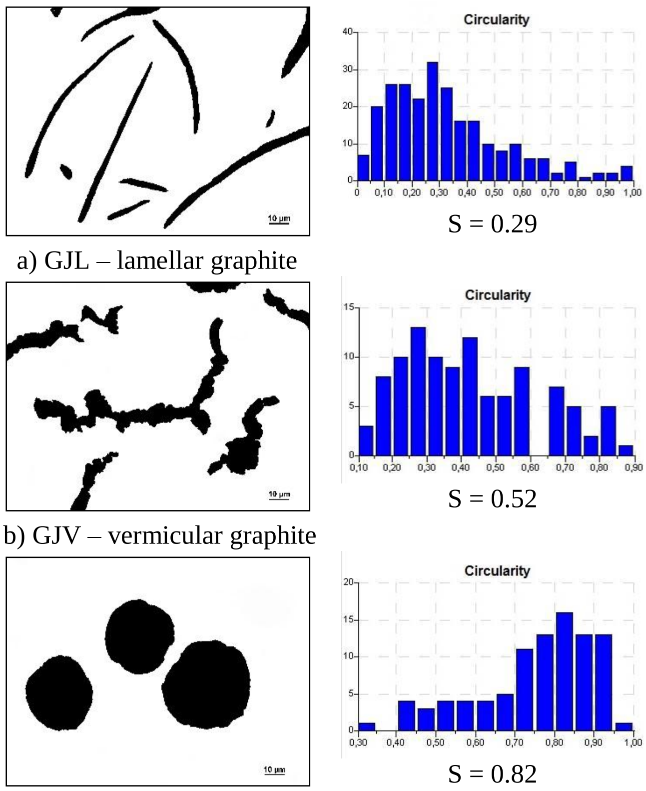
Table 3. Mechanical properties of the specimens

Specimen	R_m (MPa)	A (%)	K (J)
GJL	215	0.5	–
GJV	405	2.5	12
GJS	540	7.0	35

Source: own study

Results of evaluation of the shape factors describing the shape of lamellar, vermicular and nodular graphite in the specimens of graphitic cast irons are given in Fig. 2.

Numerical values of the shape factor increase with increasing nodularity of graphite (i.e. from lamellar through vermicular to nodular graphite). In the same sequence the mechanical properties are improved. Shape factor enables numeric description of the shape of graphite and it can be used for a mathematical formulation of dependence between microstructure and mechanical properties of graphitic cast irons.



a) GJL – lamellar graphite
b) GJV – vermicular graphite
c) GJS – nodular graphite
d) histograms and shape factor

Fig. 2. Evaluation of the shape factor (circularity)

Source: own study

4. Conclusions

Graphite as a structural component of graphitic cast irons can obtain shapes from lamellar through vermicular to nodular. The shape of graphite directly influences the mechanical properties of graphitic cast irons (they are improved with increasing nodularity of graphite). The shape factor, presented in the paper, enables to express the shape of graphite in the form of a numeric value. Consequently, it can be used for the formulation of predictive relationship between microstructure and mechanical properties of graphitic cast irons.

The same way of formulation of shape factor can be applied to other materials where some kind of shape classification is currently done visually (BELAN J. 2014, HURTALOVÁ L. 2014, HURTALOVÁ L. 2015, ULEWICZ R. 2014). It is suitable to use the automatic image analysis which provides an efficient way of measurement of the shape factor with high speed and statistical exactness.

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