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The influence of cooling rate on the hardness of cast iron with nodular and vermicular graphite

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Abstract

The paper presents hardness changes for cast iron with nodular and vermicular graphite, determined within the separately cast test blocks. Investigation has comprised cast irons with similar ferrite and pearlite fractions in the metal matrix. The hardness measurements have been performed by Brinell method for samples taken both from an edge and from the centre of a Y block (for nodular cast iron) or of a reversed U block (in the case of vermicular cast iron). Investigations have pertained both to the test parts and to the sinkheads of the test blocks. Hardness measurements have been completed with metallographic examination.

Keywords: Mechanical properties, Hardness, Cooling rate, Nodular cast iron, Vermicular cast iron

1. Introduction

The cast iron hardness depends first of all on the character of metal matrix, and to the less degree on the shape, size and quantity of graphite precipitates [1, 2]. Cast iron exhibits the lowest hardness in the case of ferritic matrix; it increases with the change of matrix to the ferritic-pearlitic, then to the pearlitic-ferritic one, and in the end to the pure pearlitic matrix [3]. The higher dispersion of pearlite along with the refining of ferrite and austenite grains result in an increase in cast iron hardness [2].

Chemical composition influences the regarded cast iron property both by determining the type and hardness of matrix and – to the less degree – by affecting the shape, quantity and size of graphite precipitates. An increase in the degree of eutectic saturation S_c causes the reduction of hardness provided that the silicon content is lower than 3% and the phosphor content is constant. The cast iron hardness is reduced with an increase of silicon content until the pure ferritic matrix is achieved (about 3% of silicon), and further increase of this element leads to the gradual growth of cast iron hardness, which is a result of strengthening of the matrix by silicon. Therefore in the case of ferritic nodular cast iron its hardness increase in a monotonic way with an increase in silicon content [1, 4].

Phosphor is an element which stabilizes pearlite, rises hardness and reduces elongation [5]. This element implies the rise in cast iron hardness due to generation of hard phosphor eutectic. Increasing the phosphor content by 1% results in the hardness growth by about 40 HB [1, 4].

As far as the nodular cast iron is concerned, increasing carbon content diminishes HB, R_m, and $R_{0,2}$ by its influence on an increase of quantity of precipitates and ferritization of matrix.

Even small changes in content of several elements, both from among the basic and the alloying ones, can significantly affect the mechanical properties of nodular cast iron of EN-GSJ-400-18U-LT grade [6] or EN-GSJ-500-7 grade [7]. A number of alloying elements have an important influence on the cast iron hardness. It rises with the increased content of carbide forming elements (chromium, molybdenum, vanadium, and manganese). Copper and nickel, in turn, contribute to the increase of hardness by increasing the pearlite content in the matrix, but to the much less degree. Titanium affects the considered cast iron property in a diverse way; added in small quantities (up to 0.08%) promotes graphitization, by the same reducing hardness, whereas up to the 0.45% it promotes the interdendritic graphite formation, and then at contents exceeding 0.5%, while acting already as the carbide forming element, leads to an increase in cast iron hardness [1, 4]. Casting wall thickness is also a significant parameter as far as hardness is concerned. Its increase – by reducing the cooling rate – causes an increase in ferrite content within the matrix, an increase in the size of eutectic cells and the length of graphite flakes (in grey cast iron), but a reduction of cementite content and pearlite dispersion [2]. So the casting cooling rate affects significantly the cast iron hardness [1]. Increased cooling rate implies refining of ferrite and austenite grains, and in the case of pearlite – an increase of its dispersion degree, what results in the increased hardness of these structural components [1,4]. The significance of test block cooling rate for the assessment of mechanical properties of nodular cast iron is clearly testified by the results described in Ref. 8. This paper states that the impact strength of the examined material changes significantly (and in quite wide temperature range) depending on the place within the test block from which an individual specimen has been taken. It is related mainly to the influence of the casting cooling rate on the matrix structure of the examined cast iron and on the quantity and size of graphite precipitates.

Examination of hardness distribution over the specified area of casting surface allows for determining the material uniformity [4].

2. Author's investigations

The purpose of investigation has been a comparison between the hardness of two cast iron types with similar ferrite and pearlite fractions in the metal matrix, however nodular graphite has occurred in the first of them, whereas vermicular graphite in the second one. Chemical compositions of the examined cast iron types are given in Table 1.

Table 1.
Chemical compositions of the examined cast iron types

Cast iron type	Chemical composition, %				
	C	Si	Mn	P	S
Nodular	3.60	2.69	0.350	0.042	0.011
Vermicular	3.25	1.92	0.189	0.050	0.019

Cast iron hardness has been determined for specimens cut out of the separately cast test blocks. The work has been also intended to determine the range of hardness changes within the test parts and sinkheads of the blocks for both types of the examined cast iron. For the nodular cast iron it has been the Y block with test part of thickness and height of the test part equal to 25 mm and 40 mm, respectively, and for vermicular cast iron the test block has got a shape of reversed U with test parts of thickness also equal to 25 mm and 50 mm high.

Two sections of about 25 mm thickness have been cut out of each test block. One of them has been taken from an edge, while the other from the centre of the block. After surface grinding a coordinate grid has been marked on it. Nodes of the grid have appointed the spots where hardness has been measured. The distances between the nearest subsequent indents as well as the distance between any indent and an edge of the specimen have met the appropriate Standard [9]. Marking of the grid on the surfaces of the examined specimens has ensured that the measurements are taken in precisely determined places and has allowed for making suitable comparisons.

The hardness has been measured by Brinell method, according to the pertinent Standard [9]. Steel ball of 5 mm diameter has served as an indenter, and the load has been equal to 7.35 kN.

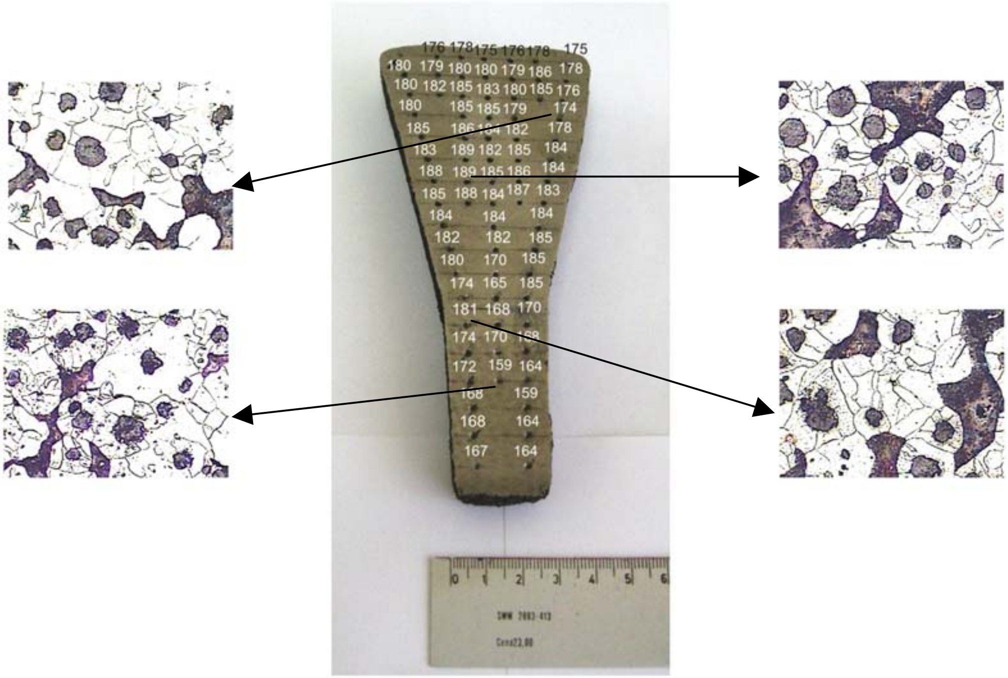
The cast iron hardness has been calculated by means of the formula [10]:

$$HB = \frac{0{,}102F}{S} = \frac{0{,}102 \cdot 2F}{\pi D(D - \sqrt{D^2 - d^2})}$$

where: F – loading force [N]; S – indent area [mm^2]; D – diameter of the indented ball [mm], d – diameter of the permanent indent on the surface of the examined item [mm].

Figures 1 and 2 present the specimens for hardness examination cut out of the nodular and the vermicular graphite, respectively, with marked measurement results. These figures show also microstructures of cast iron found in direct vicinity of nodes exhibiting the highest and the lowest hardness values, for both the test parts and the sinkheads of test blocks. The non-etched metallurgical microsections prepared after hardness examination have served for the assessment of the graphite precipitates according to the PN-EN-ISO 945 Standard [11], and then while being etched with Nital – for the assessment of pearlite and ferrite quantities (according to PN-75/H-04661 Standard [12]) occurring in respective regions of the analysed specimens. The results of metallographic examination are gathered in Table 2.

Table 3 presents data concerning results of the performed hardness measurements. Symmetric t test examining the equality of two means (at the significance level of 0.05) [13] has been applied in order to compare the average hardness of the test parts and the sinkheads in samples taken both from an edge and from the centre of each test block, as well as to compare hardness values for both nodular and vermicular graphite. The results of this test are given in Table 4.



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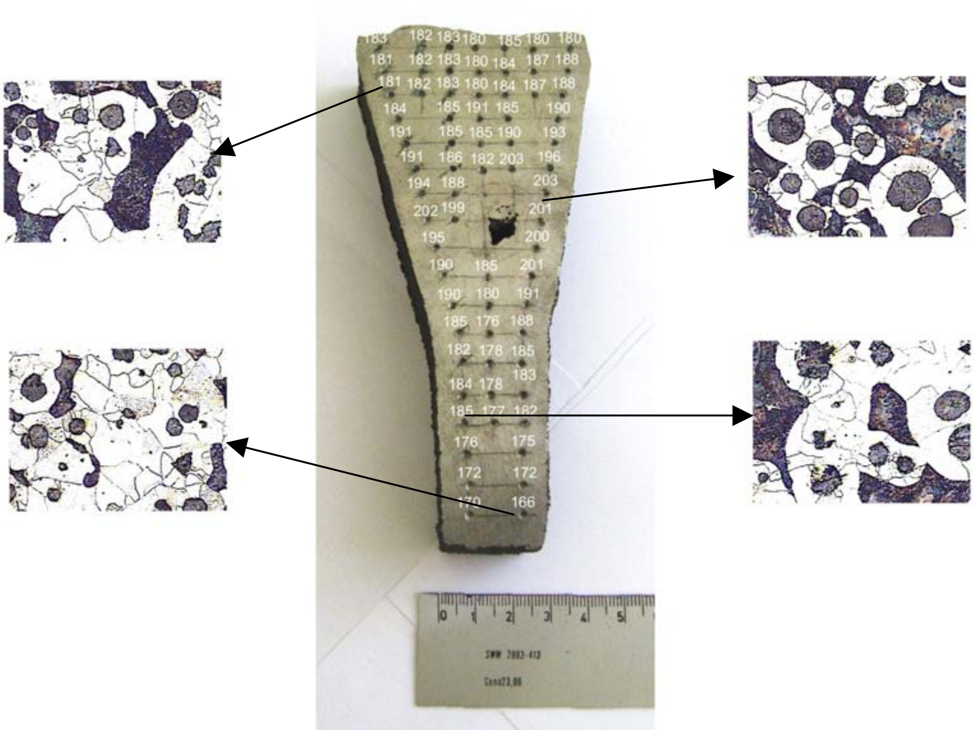

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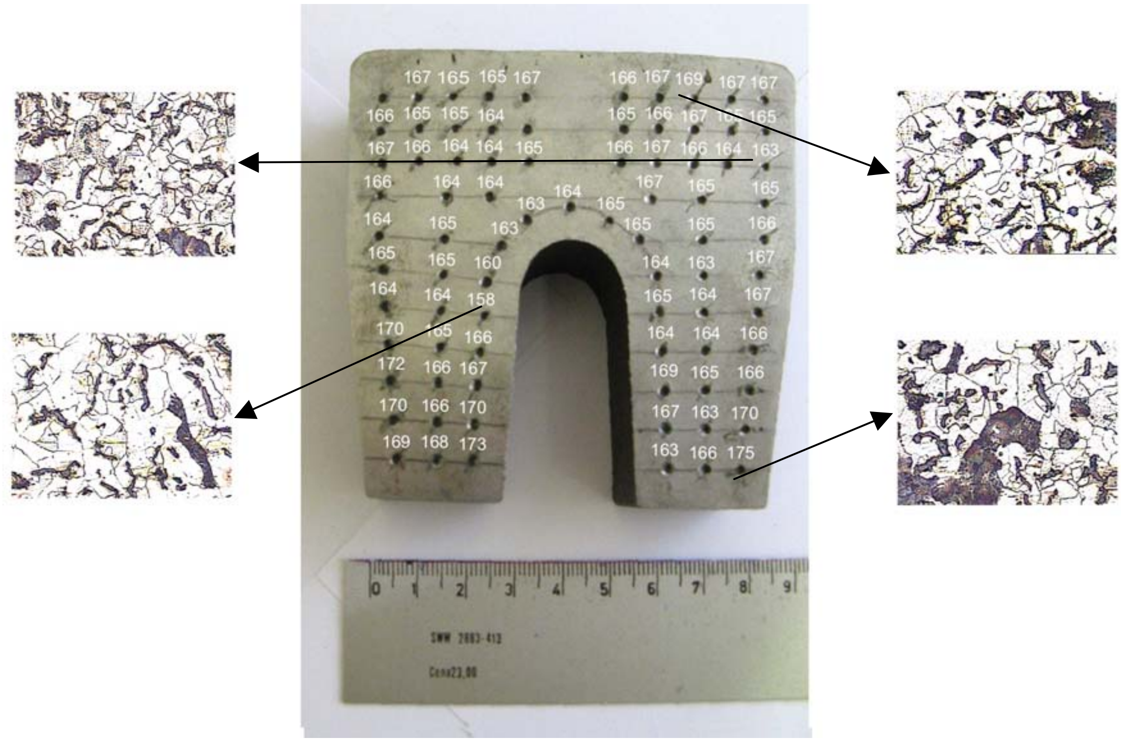
Fig. 1. Samples cut out of the test block of nodular cast iron with marked results of hardness measurements; a) the sample taken from an edge of the test block; b) the sample taken from the centre of the test block. Cast iron microstructures from regions of the lowest (left) and the highest (right) hardness are shown in the side pictures. Microsections etched with Nital, magn. 100×



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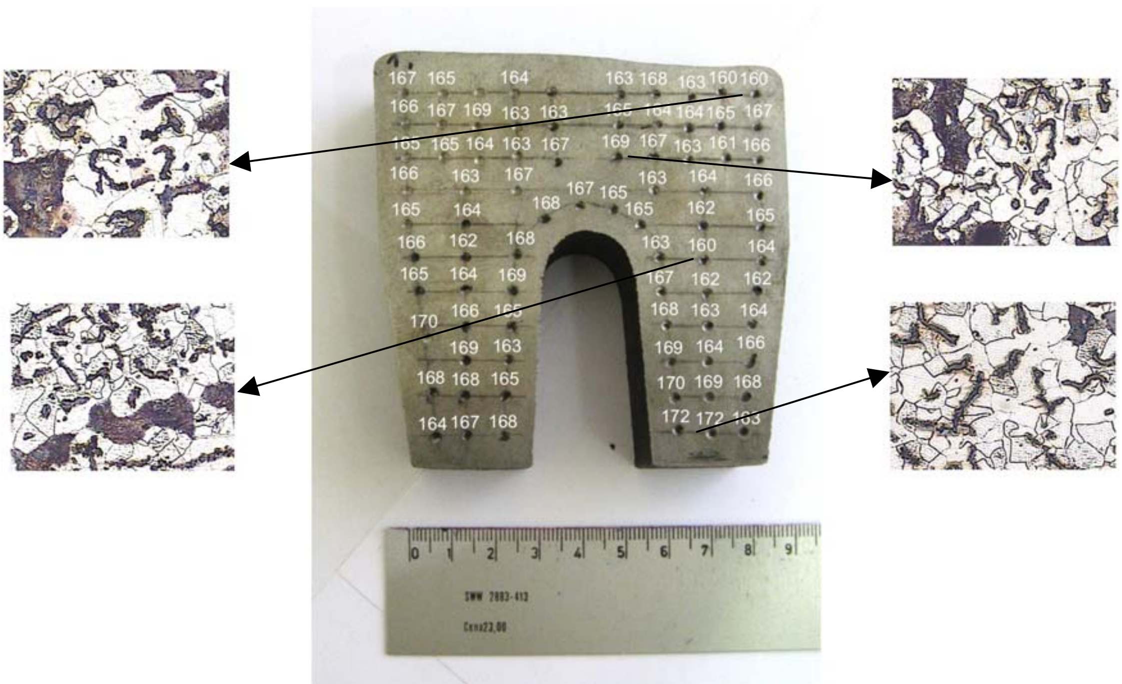

b)

Fig. 2. Samples cut out of the test block of vermicular cast iron with marked results of hardness measurements; a) the sample taken from an edge of the test block; b) the sample taken from the centre of the test block. Cast iron microstructures from regions of the lowest (left) and the highest (right) hardness are shown in the side pictures. Microsections etched with Nital, magn. 100×

Table 2.
The assessment of graphite precipitates and the matrix for the examined nodular and vermicular graphite

Type of examination	Observed near places of hardness value equal to:	Nodular cast iron				Vermicular cast iron			
		Sample 1*		Sample 2*		Sample 3*		Sample 4*	
		Test part	Sinkhead	Test part	Sinkhead	Test parts	Sinkhead	Test parts	Sinkhead
Determining the features of graphite precipitates	minimum	85%VIA7 + 15%VIA8	70%VIA5 + 30%VIA7	VIA7	70%VIA7 + 30%VIA8	98%IIIA5 + 2%VIA6	95%IIIA5 + 5%VIA6	98%IIIA4 + 2%VIA6	80%IIIA4 +20%VIA6
	maximum	80%VIA6 + 20%VIA7	70%VIA6 + 30%VIA7	VIA5	60%VIA6 + 40%VIA7	95%IIIA5 + 5%VIA6	95%IIIA5 + 5%VIA6	95%IIIA5 + 5%VIA5	IIIA4
Assessment of pearlite and ferrite quantities	minimum	P6Fe94	P6Fe94	P6Fe94	P20Fe80	P6Fe94	P6Fe94	P20Fe80	P6Fe94
	maximum	P20Fe80	P20Fe80	P20Fe80	P45Fe55	P20Fe80	P6Fe94	P20Fe80	P20Fe80

* even numbers designate samples taken from the edges, odd numbers designate samples taken from the centres of the test blocks

Table 3.
Data concerning the results of hardness examination for nodular and vermicular cast iron

Value type	Results of hardness measurement, HB							
	Nodular cast iron				Vermicular cast iron			
	Sample 1*		Sample 2*		Sample 3*		Sample 4*	
	Test part	Sinkhead	Test part	Sinkhead	Test parts	Sinkhead	Test parts	Sinkhead
minimum	159	170	166	176	158	163	160	160
maximum	185	193	188	203	175	169	172	169
mean	168.89	182.17	178.56	187.70	166.17	165.40	166.04	164.53
standard deviation	6.685	4.377	6.099	6.804	3.460	1.345	3.303	2.250

* even numbers designate samples taken from the edges, odd numbers designate samples taken from the centres of the test blocks

Table 4.
Comparison of two mean hardness values by means of the t test

values of calculated (t_{obl}) and tablicowych ($t_{0.05}$) t coefficients	1Y and 2Y test parts; 1U and 2U test parts	1Y test part-sinkhead	1Y and 2Y test parts	1Y and 2Y sinkheads	2Y test part-sinkhead	1U test part-sinkhead	1U and 2U test parts	1U i 2U sinkheads	2U test part-sinkhead
$t_{obl.}$	5.365	-7.872	-4.663	-4.946	-4.856	2.360	-0.257	1.998	1.192
$t_{0.05}$	1.96	1.96	1.96	1.96	1.96	1.96	1.96	1.96	1.96

1Y – nodular cast iron sample taken from an edge of the test block;
2Y - nodular cast iron sample taken from the centre of the test block;
1U – vermicular cast iron sample taken from an edge of the test block;
2U – vermicular cast iron sample taken from the centre of the test block

3. Summary

Analysis of the results given in Table 3 allows for stating that from the two considered cast iron types, nodular and vermicular, similar with respect to the ferrite and pearlite fractions in the alloy matrix, the nodular cast iron exhibits slightly greater hardness. This difference, however, is significant frohe statistic point of view (compare data in Table 4). The hardness of nodular cast iron, calculated as the mean value from measurements taken both from an edge and from the centre of test blocks, has been about 174 HB; the hardness of vermicular cast iron, calculated in the same way, has reached the value of about 166 HB. The average hardness determined for the sinkhead parts has been equal to 185 HB for nodular cast graphite and has been lower by 20 units in the case of vermicular cast iron.

It is characteristic that the hardness of the cast iron graphite is higher for the sample taken from the centre of the test block than for the sample cut out of its edge, both for the test part and for the sinkhead. The differences in hardness value are about 10 HB and about 5 HB, respectively. The tendency of hardness to rise towards the centre of the test block has not been recognized in the case of vermicular cast iron (compare data in Table 3), both with respect to the test part and to the sinkhead of the test block.

It should be noticed that the hardness of nodular cast iron is higher for the sinkhead than for the test part of the test block, and the differences for sample cut out of an edge and of the centre of the block are equal to about 13 HB and 9 HB, respectively. For the vermicular cast graphite such a relationship has not been found.

The results of hardness measuring are much more scattered for nodular cast iron than for vermicular cast iron. The results has fallen within the ranges of 159 – 203 HB and of 158 – 175 HB, respectively.

Analysis of Figs 1 and 2 reveals, according to expectations, that the higher hardness values for both nodular and vermicular cast iron has occurred in regions characterised by an increased pearlite fraction.

It can be supposed that lower hardness values observed in the test part, as compared to the values recorded for the sinkhead, of nodular cast iron test block, as well as the lower hardness of the ‘edge’ sample as compared to the ‘central’ sample, are related to the more intensive heat outflow, and by the same to the more intensive inoculation and crystallization of the nodular graphite precipitates, and related to them increased susceptibility of cast iron to matrix ferritization. The lack of similar dependency for the vermicular cast iron can result from the different crystallization mechanism for that type of graphite precipitates. It should be, however, stated in general that as far as the hardness is concerned, the vermicular cast iron exhibits less susceptibility to the cooling rate than the cast iron containing nodular graphite.

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