STUDIES OF THICK-WALL DUCTILE IRON CASTINGS IN TERMS OF HETEROGENEITY OF THE STRUCTURE AND MECHANICAL PROPERTIES

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Abstract

The paper presents a study of the chemical composition and selected thermal operations on uniformity of the structure and properties of 75 mm thick cast iron (casting mould YIV). HB hardness distribution was investigated on cross-section of the samples. R_{p02}, R_m, A_5 was determined from tensile specimens cut from the centre and outer sections of the casting YIV. Samples were taken from two plates cut at intervals of 25 mm from the bottom of the casting. Metallographic microsections were made of the grip sections of the tensile specimens. It was found that the applied heat treatment ferritizing annealing, normalizing and the additive alloy (Cu) reduce differences in mechanical properties and structure of matrix in thick-walled castings.

Keywords: Thick-walled castings, cast iron, heterogeneity, structure, mechanical properties

1. INTRODUCTION

The worldwide increase in use of ductile iron casting can be observed constantly. Over the last few years there was an increase of interest in thin and thick wall ductile iron casting solidification. Metallurgical examination after solidification and cooling to room temperature were the main subject of studies. This includes a phase transformation during cooling process.

Typical commercial ductile cast iron in cast condition have a microstructure of spheroidal graphite, ferrite and perlite matrix. This microstructure has significant importance on mechanical properties [1].

During the stable eutectoid reaction, austenite decomposes into ferrite and graphite. At the graphite/austenite interface the ferrite is nucleating and grows symmetrically around the spheroidal graphite, as the ferritic reaction undergoes. Diffusion of carbon through the ferrite shell controls this growth. Therefore this is quite a slow process and the temperature of the metastable eutectoid might be reached before the complete transformation of austenite [2].

Increase of weight and wall-thickness of the cast iron castings impair several mechanical properties especially elongation. That degeneration of graphite morphology in the thermal centre of heavily wall-thick ductile cast iron castings is often caused magnesium fading and chemistry segregation. This is the reason for a difference in mechanical properties between the test coupons separately cast and the samples cut from the heavy castings. That results in difficulty of obtaining a reliability of ductile cast iron castings. There has been little systematic research in heavy castings, although this degradation is presumed to be related to the microstructural change through the wall-thickness. [1- 6].

The current paper presents the results of ferritizing annealing and normalizing of thick wall ductile cast iron castings.

2. EXPERIMENTAL PROCEDURES

For the verification of the thesis, the hardness distribution, mechanical properties (Rm, Rp0,2, A5) were determined and the microstructure on cross sections of standard YIV castings with a wall thickness of 75 mm was evaluated. The homogeneity of the analyzed properties was determined by statistical methods.

Research material

Two types of ductile cast iron were used for the study: non-alloyed cast iron and copper alloyed cast iron. The chemical composition of the cast iron is shown in **Table 1**. Fusible ingots of EN-GJS-400-15 (non-alloyed) ferritic iron and perlitic-ferritic EN-GJS-600-03 (copper) were made in the Foundry "Śrem" S.A. They were cast into YIV sample molds (wall thickness 75 mm). **Figure 1** shows the size of the test sample (according to PN-EN 1563: 2012). **Figure 2** shows the method of cutting the samples for testing. The basic mechanical properties of cast iron and critical temperatures are shown in **Table 2**.

Table 1 Chemical composition [wt. %]

Cast iron	C	Si	Mn	P	S	Cr	Cu	Ti
non-alloyed	3.82	3.21	0.17	0.059	0.019	0.01	0.12	0.19
alloyed	3.39	2.62	0.29	0.042	0.010	-	0.51	-
	Mg	Ni	Mo	V	Al		K_G	S_c
non-alloyed	0.047	0.008	0.002	0.009	0.0026		12.10	1.18
alloyed	0.046	0.72	-	-	-		-	-

Table 2 Mechanical properties and critical temperatures of ductile cast iron

Cast iron	R_m MPa	A_5 %	Hardness HB	Ac_{11}	Ac_{12}	Ar_{11}	Ar_{12}	T_{gr}
non-alloyed	471.0	13.0	171.0	855.0	911.5	818.0	743.0	768.5
alloyed	603.0	2.9	233.6	834.3	893.3	798.0	732.7	715.3

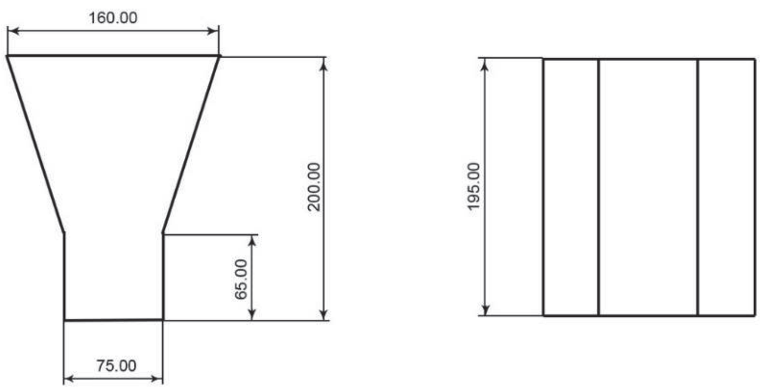


Figure 1 Dimensions of the test ingot YIV (PN-EN 1563:2012)

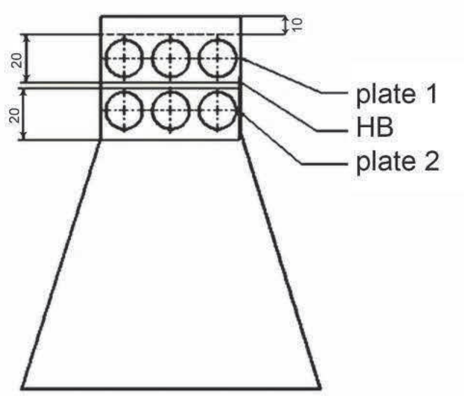


Figure 2 Plates cutting method

Heat treatment

Only non-alloyed cast iron was processed. Ferritizing annealing and normalization were performed. The heat treatment was carried out in a PSK7 furnace, whose accuracy was ± 5 °C. The ferritizing annealing scheme is shown in **Figure 3a**, and the normalization in **Figure 3b**.

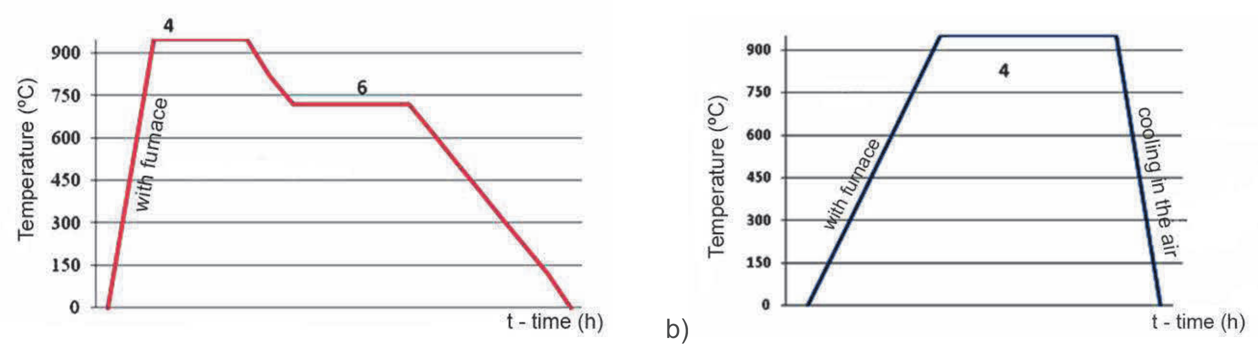


Figure 3 Diagram of the heat treatment: a) ferritizing annealing, b) normalizing

2. RESULTS

Hardness measurements were made on the cut plates. Measuring trace is visible in **Figure 4**. **Table 3** show average measurement results of no-alloyed cast iron after ferritizing annealing and normalizing. **Figure 5** show distribution of hardness on plates

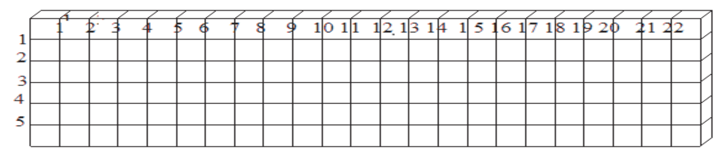


Figure 4 Scheme of distribution of measuring points on cut plates

Table 3 Results of hardness measurements

Cast iron	State after:	Hardness HB/ no. of horizontal measurement trace				
		1	2	3	4	5
non-alloyed	casting	169,80	169,59	168,25	168,35	168,55
	ferritizing	163,63	163,45	163,39	163,62	163,66
	normalizing	247,77	247,70	247,51	247,55	247,83
alloyed	casting	243,52	243,84	244,07	243,70	243,43

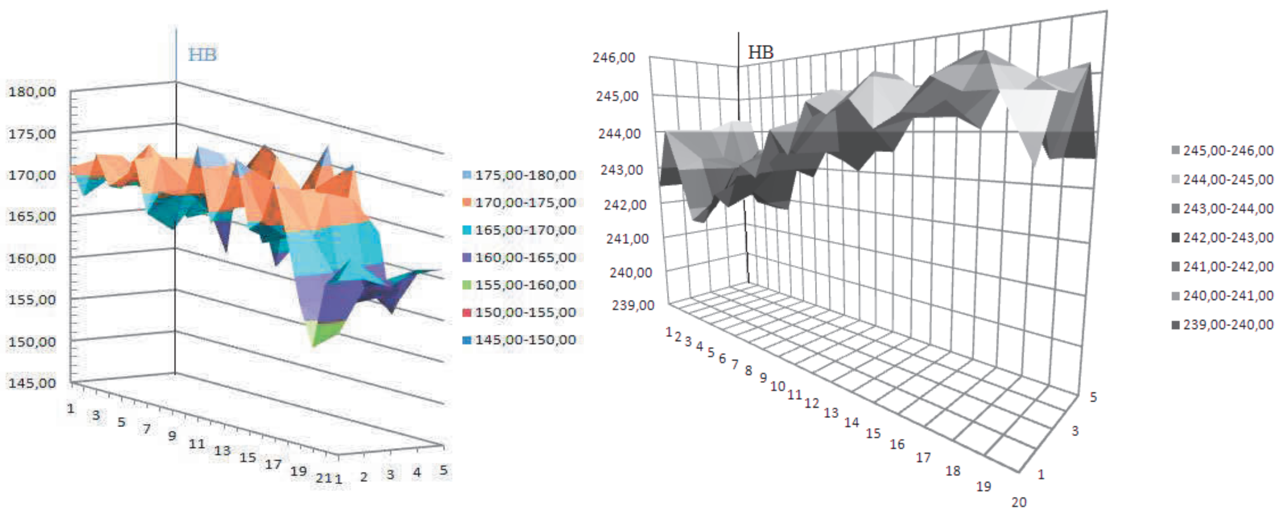


Figure 5 Distribution of hardness after: a) casting non-alloy cast iron, b) casting copper alloy

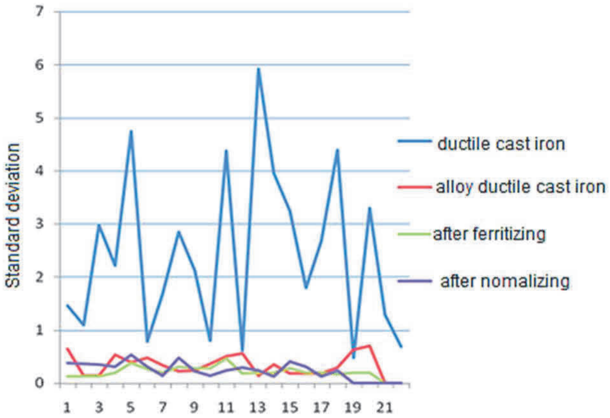
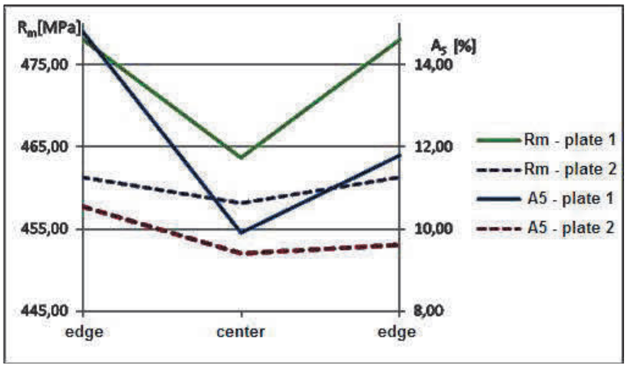
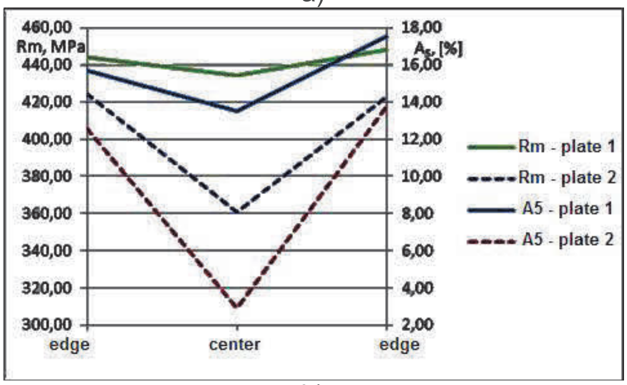


Figure 6 Comparison of standard deviations of the hardness measurement



a)



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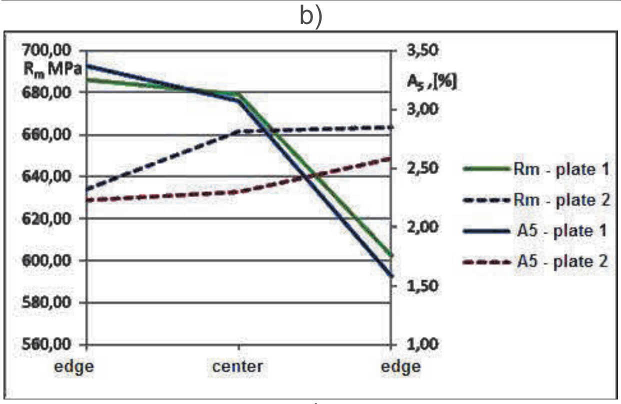

c)

Figure 7 Relationship of Rm and A5 on the position on the plate of non-alloyed cast iron after: a) casting, b) ferritizing annealing, c) normalizing

Tensile tests were performed on the INSTRON 8502. The test was carried out on fivefold strength sample with a diameter of 10 mm. **Table 4** shows the values of A5, Rm and R0.2 read from the graphs.

3. DISCUSSION

Non-alloyed cast iron has a ferritic-perlite structure with a content of about 15 % perlite. Alloy cast iron structure was pearlite-ferrite content of about 20 % ferrite.

The hardness of non-alloyed cast iron ranged from 157.1 to 177.3 HB after casting. Ferritizing annealing caused a decrease in average hardness by about 5 HB units relative to the state after casting. Normalizing showed a significant increase in hardness and ranged from 246.7 to 247.5 HB.

Table 4 Results of the tensile test of researched cast iron after casting, ferritizing annealing and normalizing

Cast iron	State after:	Parameter:	A_5, %	R_m, MPa	$R_{0.2}$ MPa
non-alloyed	casting	average	11.01	466.70	357.20
		standard deviation	2.05	8.94	1.43
	ferritizing annealing	average	12.65	422.30	339.52
		standard deviation	5.09	29.15	7.93
	normalizing	average	2.52	654.25	503.23
		standard deviation	0.64	31.30	6.80
alloyed	casting	average	2.98	590.30	449.95
		standard deviation	0.84	37.37	7.51

Differences in average hardness after heat treatment are a straightforward consequence of the structural state of the metallic cast iron matrix. Ferritizing annealing results in a decrease in perlite by about 3 %. Reduction of hard perlite content from about 15 % to about 3 % due to ferritizing annealing results in a decrease in hardness. Normalizing causes significant increase in the perlite content by about 70 % in comparison to the state obtained after casting. Therefore, a general increase in hardness of about 80 HB is observed. The average hardness of alloy cast iron is 244 HB and is very close to the values of non-alloyed cast iron after normalizing.

In the evaluation of homogeneity of the hardness on the casting section, the statistical parameter - standard deviation (**Figure 6**) is decisive. Non-alloyed cast iron after the casting shows the largest scatter around average hardness. Each heat treatment and the addition of Cu in alloy cast iron significantly reduces the standard deviation of the analysed property.

Iron after the casting has the structure resulting from primary and secondary crystallization (solid state). In thick-walled castings, chemical microsegregation and structural segregation are strong. This adversely affects all properties of castings. Segregation in thick-walled castings and changes in graphite shape determine the degree of heterogeneity of the structure, and consequently the properties of the cast. The only way to reduce microsegregation in castings is heat treatment. The heat treatment used in the work (**Figure 3**) include an austenitizing treatment. During this process homogenizing of the cast iron matrix metal occurs and especially the equalization of silicon and manganese concentration.

Alloyed cast iron, after casting, has a much greater homogenity in hardness distribution than non-alloy cast iron (**Figure 5**). The copper addition induces general perlitization of the matrix and shows reverse segregation.

Based on the results of the mechanical properties test (**Figure 7**) it can be stated that the value of the elongation A5 in non-alloyed cast iron, after the casting, is in the range of 9.90 % to 14.82 % for plate 1. For plate 2, value range from 9.40 % to 10.54 %. After the ferritizing annealing of non-alloy cast iron, the value of elongation A5 for plate 1 is 13.49 % to 17.50 %, and for plate 2 is from 2.89 % to 13.75 %.

It has been observed for non-alloyed cast iron in both states: after castings and after ferritizing annealing, that elongation A5 has the highest values at the edges of plate 1 due to the crystallization rate. Values of A5 indicate that in this cast iron there is a ferritic-perlite matrix structure. In non-alloyed cast iron after ferritizing annealing an increase in elongation was observed in comparison to cast iron after casting, due to the reduction of hard pearlite.

However, for non-alloyed iron after normalizing elongation A5 has an average value, for both plates, around 2.52 %, and the decrease is caused by the formation of perlite matrix.

The elongation value for alloyed cast iron (**Tables 3** and **4**) is 2.98 % and is very close to A5 of non-alloyed cast iron after normalizing. In alloyed cast iron, the highest values are in the middle of the plate 1.

Based on the results of the distribution of, the following observations can be made:

- The average R_m value for non-alloyed cast iron after casting is 466.77 MPa and the highest values are observed at the edge of the plate,
- For non-alloyed cast iron after ferritizing annealing, a 10 % lower R_m value is observed in comparison to cast iron after casting,
- Non-alloyed cast iron after ferritizing annealing have the value of R_m higher by 187.55 MPa in comparison to cast iron after casting (no relationship),
- Alloyed cast iron and non-alloyed cast iron after normalizing have a similar range of values of $R_{m.}$ The highest value is observed in the center of the plate. The addition of copper inhibited the growth of graphite.

Heat treatment of ductile cast iron enables the formation of matrix structure in a very wide range.

The mechanical strength of ductile cast iron is mostly influenced by shape and size of the graphite and, to a lesser extent, its distribution. Heat treatment has no significant effect on the distribution, size and shape of the graphite. Graphite stereometric features strongly influence the properties of cast iron. The solidification zones at the end of the liquid are enriched with additives deforming the graphite. This affects the level of homogeneity and mechanical properties.

4. CONCLUSSION

Based on the conducted research and analysis of results, the following conclusions can be drawn:

- The largest heterogeneity on castings at the cross-section of a thick-walled cast occurs in non-alloyed cast iron,
- Heterogeneity of hardness can be significantly reduced by heat treatment with high temperature treatment, long-lasting austenitization, during which there is a reduction in micro-segregation and structural segregation,
- An effective way to limit the heterogeneity of properties in thick-walled castings is the addition of copper,
- The mechanical properties R_m, $R_{p0,2}$, A_5, are dependent on where the sample is taken from the thick-walled cast. The higher the cooling rate during crystallization, the better their values are.
- In further studies the heterogeneity of the thick-walled castings of ductile cast iron, a quantitative assessment of the graphite and matrix composition in relation to mechanical properties would be required.

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