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The effect of cooling rate on the microstructure of nodular cast iron

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Abstract

The study gives the results of the investigations concerning an effect of the casting cooling rate (casting made from nodular iron used as a starting material for austempering to produce ADI) on the morphology of nodular graphite and metallic matrix composition. The features of the microstructure morphology were determined on a LUCIA computer program using castings of 10, 20, 40 and 60 mm diameter. It has been proved that increasing the casting diameter from 10 to 60 mm (i.e. reducing the cooling rate) increases the content of graphite from 10 to 12% and an average area of the precipitations from about 150 to 440 μm^2, while it reduces the number of the graphite precipitations in 1 mm^2 from about 700 to 260, the mean value of the shape factor from 0,96 to 0,84, and pearlite content in the matrix from about 96% to 84%. The chemical composition seems to have no significant effect, the only exception being Mo whose presence increases in a visible way pearlite content in the matrix at each cooling rate. The obtained results, and specifically the distribution of the frequencies of occurrence of the examined morphological features of graphite, confirm the vast possibilities that the LUCIA computer program of image analysis offers in evaluation of the effect of technological parameters on cast iron microstructure.

Keywords: Casting processes, Cooling rate, Microstructure, Pearlite, Graphite, Circularity

1. Introduction

New materials developed at the end of the 20th century include the austempered ductile iron (ADI), which offers an exceptionally beneficial combination of the mechanical and plastic properties [1-3]. A very important factor, on which the ADI properties after heat treatment largely depend, is the microstructure of the base nodular iron, and specifically the amount, size and distribution of nodular graphite in the matrix as well as the composition of the metallic matrix, viz. the content of pearlite and ferrite. Increasing the number of graphite precipitations in a pearlitic-ferritic nodular iron heat treated to make ADI from 100 to 230 per mm^2 improves its tensile strength, toughness and impact resistance, while keeping hardness at the same level [4, 5]. The large number of the graphite precipitations means smaller spacing between them and more uniform composition of the metallic matrix. Controlling the morphology of both nodular graphite and metallic matrix is possible through proper choice of the base cast iron chemical composition and casting cooling rate. This trend suits particularly well the technology of making ADI. The study presents the results of the investigations of the morphological features of casting microstructure when different casting cooling rates are applied and the base material for castings is nodular iron with an addition of Ni, Cu and Mo. The studies were conducted on a LUCIA computer program.

2. Materials and methods of investigation

The chemical composition of the examined nodular cast iron is given in Table 1.

Table 1.
The chemical composition of nodular cast iron

Symbol	content , wt %						
	C	Si	Mn	Mg	Ni	Cu	Mo
01-B	3,75	2,55	0,19	0,08	1,45	0,62	-
02-B	3,75	2,80	0,17	0,04	0,80	0,50	0,16

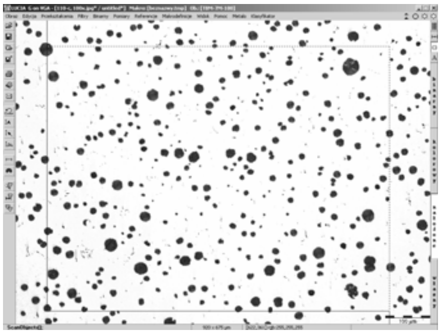
Melting was conducted in an induction, medium-frequency, acid-lined crucible furnace of 100kV power and 50 kg capacity. The operations of spheroidising and inoculation treatment were done in the furnace crucible using FeNi Mg18 (18%Mg) master alloy in an amount of 1,2% and FeSi75T ferrosilicon in an amount of 1% in respect of the melt weight. The temperature of spheroidising was 1400^0C, and that of pouring - 1370^oC. Moulds were prepared from the silica sand composition with bentonite binder and an addition of coal dust. Bars of 10, 20, 30 and 40 mm diameter were cast and were next used as polished cross-sections for the metallographic examinations. The selected morphological features of microstructural constituents were examined on a LUCIA v. 4.82 computer program. The investigations were made at the Department of Ferrous Alloys in Foundry Research Institute, Cracow. The operation of LUCIA program consists in counting of pixels selected in the examined image and converting them next by means of relevant algorithms into the numerically expressed parameters. A raster image as obtained directly from the digital camera or scanner (here conventionally called "colour image") is not suitable for analysis; it has to be transformed into a binary image, which will unambiguously define the examined microstructural constituent (or constituents). Proper measurements are taken using commands in menu *Measurement*. To obtain data expressed in metric units, and specifically in µm, it is necessary to make previous calibrations and obtain a conversion factor valid for the specific image, i.e. the number of µm/pixel.

The features of graphite morphology (surface fraction, number of precipitations, mean area, shape factor) were examined on unetched specimens, while the constitution of matrix (the content of pearlite and ferrite) was determined on the specimens etched with Mi-1Fe reagent.

3. The results of investigations

Microstructure was examined under a NEOPHOT 32 metallographic microscope using polished cross-sections unetched (examinations of graphite) and etched in Mi1Fe reagent (4% nital) according to the Polish Standard PN-61/H-04503 (examinations of matrix).

The examined areas were surrounded by a measuring frame. When all objects situated within the frame are analysed, the results obtained for each selected property are expressed as a set of the following data: mean, standard deviation, minimum/maximum value. For each selected feature of morphology, its characteristics can be expressed in the form of a diagram with plotted distribution of the number of objects within the whole range of their occurrence. An example of the micrography and the results of graphite morphology evaluation for a 10 mm diameter casting made from the 01-B cast iron are shown in Figure 1. Fine impurities (in preselected size ranges) were eliminated (de-marked) using function *Erase*, and thus were not included in the analysis and evaluation. Examples of distribution of the frequencies of occurrence of the graphite precipitations of given surface and shape factor values in castings of 10 and 60 mm diameter (01-B cast iron) are shown in Figures 2 and 3.



Measurement surface	1790400 µm^2
Number of precipitations, 1/mm^2	655
Content of graphite	10%

Property	**mean**	**s.d..**	**min.v.**	**max.v.**
Surface of graphite	152,7	133,9	8,89	1140,1
Perimeter	42,1	19,2	10,43	143,9
Circularity	0,932	0,105	0,343	1

Fig. 1. The screen of LUCIA program and the results of measurements for 01-B cast iron, casting of ϕ 10 mm

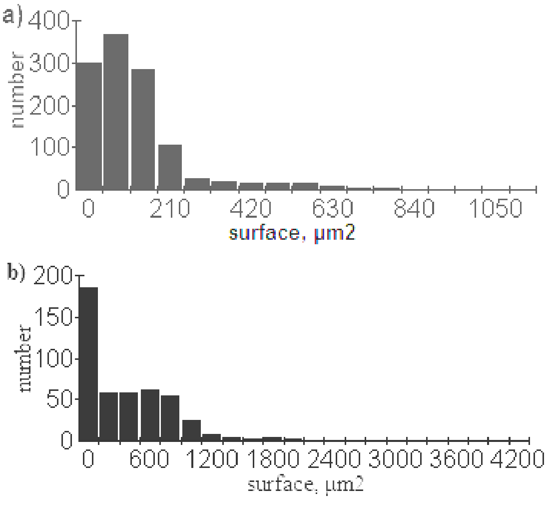


Fig. 2. Distribution of average area of the graphite precipitations: a) casting of ϕ 10 mm, b) casting of ϕ 60 mm

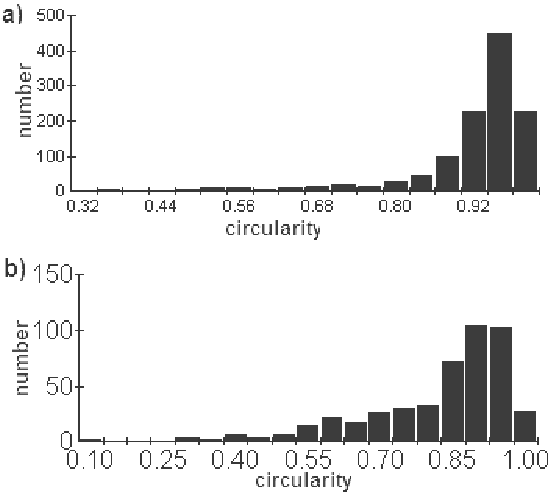


Fig. 3. Distribution of circularity of the graphite precipitations: a) casting of ϕ 10 mm, b) casting of ϕ 60 mm

4. Discussion of results

Basing on the results of the computer image analysis carried out on a LUCIA program, for analysis of the cooling rate effect on cast iron microstructure, the following parameters describing the morphological features of microstructure were selected:

- graphite content in cast iron, %,
- graphite precipitations number per 1 mm^2,
- average graphite area, μm^2,
- mean value of shape factor,
- pearlite content.

The results of these measurements are shown in Figures 4 to 8.

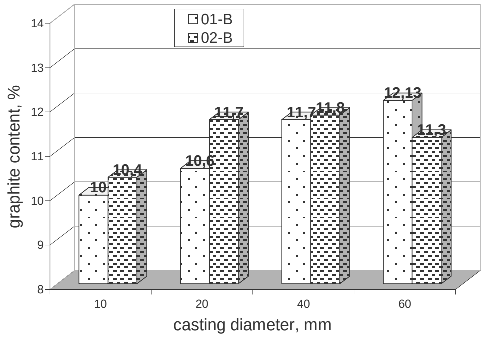


Fig. 4. Influence of casting diameter on graphite content

As follows from Figure 4, the content of graphite in cast iron decreases with increasing cooling rate of castings. For 01-B cast iron, the difference in graphite content between castings of 60 mm and 10 mm diameter is 2%. On the other hand, for 02-B cast iron this difference is 1,5%. So, the question arises what causes this difference, since both grades of the cast iron have the same content of carbon, i.e. 3,75%. During eutectic transformation, the precipitations of graphite form a liquid phase. With high cooling rate (casting of 10 mm diameter), the system faces undercooling which makes the eutectic point E shift (under stable conditions) towards higher carbon content. Due to this, the cast iron "becomes" more hypoeutectic [6, 7]. This is the reason why during solidification we have precipitation of a stable eutectic characterised by lower content of carbon and higher content of austenite. In castings of large diameters, the undercooling of liquid assumes much lower values, and therefore shifting of point E to the right is also less prominent. This means that the eutectic will have more precipitations of carbon and less of austenite. As shown in Figure 5, increasing of the cooling rate has a similar effect on the number of the graphite precipitations.

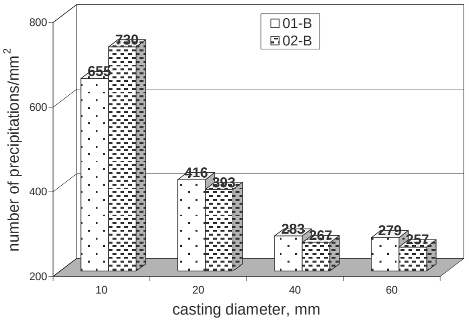


Fig. 5. Influence of casting diameter on a number of the graphite precipitations

The increase in the number of graphite precipitations assumes an exponential course along with the increasing casting cooling rate. In castings of 40 and 60 mm diameters, the difference in the number of precipitations decreases quite obviously. This effect is due to the higher undercooling and its effect on the formation of a large number of the graphite nuclei. So, in casting of 10 mm diameter, whose cooling rate assumes the highest values, the number of the graphite precipitations in a unit area will exceed 2 to 3 times the number of the precipitations obtained in casting of 60 mm diameter. The effect of cooling rate on the value of an average area of the precipitations (Fig. 6) depends also on the degree of undercooling and the rate of eutectic transformation. With low undercooling, less of graphite nuclei are formed, and their growth is not so much restrained, specially when the eutectic reaction starts proceeding more slowly. This mainly occurs in castings of 40 and 60 mm diameter.

The most important morphological feature of graphite is its shape. The best properties of cast iron are obtained when the graphite is of a perfectly circular shape, in which case the shape factor assumes the value 1. From Figure 7 it follows that for the highest casting cooling rates the shape factor assumes the values close to 1.

This phenomenon can be explained also in terms of the undercooling, increasing the number of graphite nuclei, and high solidification rate which counteracts the degeneration of graphite shape. The effect of despheroidisers and surface tension changing during solidification should be allowed for as well. Prolongation of the solidification time promotes further these adverse effects.

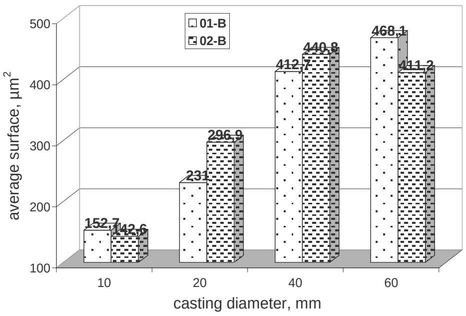


Fig. 6. Influence of casting diameter on an average surface of the graphite precipitations

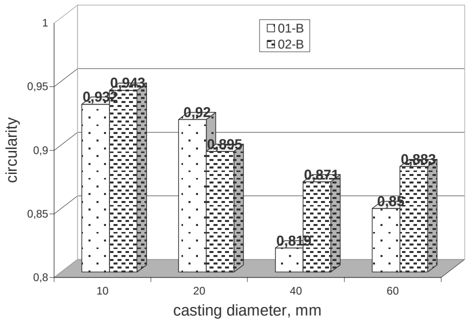


Fig. 7. Influence of casting diameter on a circularity of the graphite precipitations

Figure 8 shows the effect of cooling rate on the content of pearlite in cast iron matrix. This is related with the formation of eutectic composition during cast iron solidification. Large volumes of austenite in castings rapidly solidifying during transformation give large amounts of pearlite.

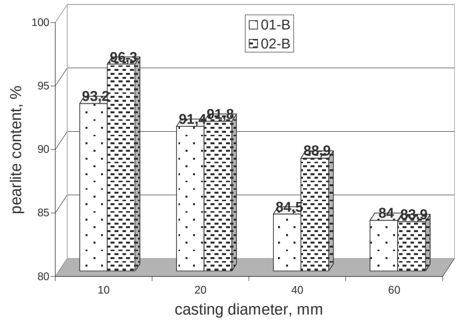


Fig. 8. Influence of casting diameter on a pearlite content in metallic matrix

An additional factor favouring the course of transformation under metastable conditions, and hence the formation of pearlite, is the high degree of undercoling due to a high rate of the heat transfer in castings of smaller diameters. In 02-B cast iron one should additionally allow for the effect of molybdenum on the course of the eutectoid transformation. Molybdenum is the element considerably improving the hardenability of ferrous alloys, mainly because of the effect it exerts on shifting of the TTT curve towards longer times of the beginning and end of transformation. This is the reason why it is easier to obtain pearlite (bainite even) in castings at lower cooling rates

5. Summary

The microstructure of nodular cast iron plays a very important role in the process of the ausferritic matrix formation in ADI. Castings usually vary in their wall thicknesses, and therefore it is necessary to investigate what effect the cooling rate has on the formation of cast iron microstructure. This is specially important for the determination of an effect that this rate may have on some morphological features of graphite, like the volume, number and area of precipitations, and the shape and composition of metallic matrix. Increasing the graphite nodule count in a pearlitic-ferritic nodular graphite cast iron heat treated to produce ADI considerably improves its tensile strength, toughness and impact resistance [4, 5]. Higher nodule count means smaller size of the crystallisation products and less differentiated phase constitution. In this study it has been demonstrated that LUCIA - a computer program for image analysis is a very precious tool for highly reliable, quantitative evaluation of the nodular cast iron microstructure.

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