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Investigations of Ferritic Nodular Cast Iron Containing About 5-6% Aluminium

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Abstract

The work presents results of investigations concerning the production of cast iron containing about 5-6% aluminium, with the ferritic matrix in the as-cast state and nodular or vermicular graphite precipitates. The examined cast iron came from six melts produced under the laboratory conditions. It contained aluminium in the amount of 5.15% to 6.02% (carbon in the amount of 2.41% to 2.87%, silicon in the amount of 4.50% to 5.30%, and manganese in the amount of 0.12% to 0.14%). After its treatment with cerium mixture and graphitization with ferrosilicon (75% Si), only nodular and vermicular graphite precipitates were achieved in the examined cast iron. Moreover, it is possible to achieve the alloy of pure ferritic matrix, even after the spheroidizing treatment, when both the aluminium and the silicon occur in cast iron in amounts of about 5.2÷5.3%.

Keywords: Innovative foundry technologies and materials, Metallography, Al-alloyed cast iron, Spheroidization, Graphite precipitates

1. Introduction

Aluminium is one of basic, relatively cheap alloying additions, introduced to cast iron mainly in order to increase its fire resistance [1-5]. Is should be noticed that the allowable working temperature of aluminium cast iron elements increases with an increase in this alloying element content. It results from the fact that aluminium both rises the temperature of generation of the most harmful layer in the scale (i.e. wüstite) [1] and increases the temperature of the eutectoid transformation [2, 6]. On the other hand, the fire resistance of cast iron depends on the shape and size of graphite precipitates, and the negative influence of graphite is intensified with an increase in the size of its precipitates [3]. The most desirable forms of graphite are very small precipitates, nodular or vermicular, occurring in the structure. The presence of such forms reduces the cast iron susceptibility to internal oxidation or swelling [7].

Former reports, including Refs. [5, 8-9], state that the low-aluminium cast iron with increased silicon content, in which graphite occurs in the nodular and vermicular form, can work in oxidizing atmosphere at the temperature up to 700-750°C.

Although aluminium influences negatively the crystallization of nodular graphite, it is possible to obtain aluminium cast iron containing both nodular and vermicular graphite precipitates, the shape of which is advantageous with respect to the fire resistance of the material [10]. It should be stressed that thanks to the increased silicon content in cast iron containing about 3% aluminium, the one-phase as-cast ferritic structure is obtained (already in specimens of 20 mm diameter), which advantageously influences the cast iron high temperature oxidation resistance.

As a continuation of previous investigations centred on the spheroidization of cast iron containing small amounts of aluminium [10-20], it was recognised as advisable to determine if it is possible to produce cast iron containing about 5-6% aluminium and compact graphite precipitates (nodular or vermicular), which would exhibit ferritic matrix in the as-cast

state. It was expected that such material should exhibit even greater fire resistance than the low-aluminium silicon cast iron with compact graphite containing about 3% aluminium [5]. As a matter of fact, Ref. [16] concerns materials including cast iron from four melts, which contain aluminium in similar amounts, namely from 4.67% to 5.90% (C=2.57÷2.71%, Si=3.50÷3.87%, Mn=0.10÷0.11%, S=0.010÷0.018%, P=0.041÷0.052%). This cast iron, treated with cerium mixture added in amount of 0.11% and graphitized with ferrosilicon introduced in amount of 1.29% (both values given with respect to the total mass of melted cast iron) was characterised by vermicular and nodular graphite, but the ferritic matrix did not occur in the as-cast state in any of the produced alloys. The desired set of properties was not achieved either during the experiments reported in [19]. In this case, cast iron (containing Al=4.69%, C=2.82%, Si=4.57%, Mn=0.10%, S=0.001% i P=0.022%) was treated with slightly greater amount of cerium mixture (0.14%) and ferrosilicon (1.4% of total cast iron mass). Pure ferritic matrix was achieved, but the nodular graphite precipitates were accompanied by a great amount of tiny chunky graphite. Such a result could be related to the amount of cerium mixture used for treatment reported in [19], which was greater than the amount used during the investigations reported in [16] (0.14% versus 0.11%).

2. Authors' investigations

The purpose of investigations was to find the basic chemical composition of cast iron which – while containing about 5-6% of aluminium – would exhibit the pure ferritic matrix in the as-cast state or would contain only relatively small pearlitic regions, and the observed graphite precipitates would occur in the nodular or the vermicular form (chunky graphite not allowed). It was assumed that the examined cast iron would be treated with cerium mixture and ferrosilicon introduced into the alloy in such proportion as the one applied in the case of the low-aluminium silicon cast iron reported in [10], i.e. 0.11% and 1.29% of total cast iron mass, respectively.

The experimental cast iron melting was carried out by means of a laboratory induction furnace, its inductor supplied with 10kHz frequency AC from the thyristor converter of the Leybold-Heraeus IS 1/III-type induction vacuum furnace. Specific type of crucibles of about 2.5 kg capacity, made of heat-resistant concrete (neutral material), was used for melting the charge. A series of six melts was prepared in a similar way. The fragmented ferrosilicon was placed at the bottom of the crucible (in order to increase the silicon content to the desired level), then cast iron scrap was put in. After achieving the liquid state, the melt was mixed with steel rod and heated up to the temperature of 1400°C. After skimming off the slag, aluminium was inserted under the metal mirror (by means of a steel rod). Then the melt was mixed again and – after about 4 minutes from the introduction of aluminium – the cerium mixture was added to the crucible. Another mixing took place, and after 4.5-5.5 minutes from the moment of cerium mixture adding, the formerly roasted ferrosilicon (75% Si) was introduced (grain size 2-4 mm). The temperature during the graphitizing modification was about 1360-1370°C. The melt was mixed again and after the subsequent 4-5 minutes poured directly from the crucible into sand moulds made of self-hardening material bonded with sodium silicate. Rod specimens in the shape of truncated cones were cast, their diameter being 20 mm halfway along their test parts. The specimens met the conditions of a semi-infinite cylinder. The sinkhead was applied to provide the necessary feeding for the nodular graphite iron castings. The shape and dimensions of cast specimens were given in detail e.g. in Ref. [16].

The series of experimental melts was divided into two groups with respect to the amount of added ferrosilicon (75% Si): during the first three melting operations the ferrosilicon was added in the amount of 75 g, while the amount of added aluminium was changed (and equal to 126g, 135 g, and 145 g, respectively). Next three melts were prepared with the ferrosilicon addition increased to 82 g, and the amounts of aluminium were changed in the same manner as in the previous three melts.

Tables 1 and 2 present chemical compositions of cerium mixture and ferrosilicon, respectively. Table 3 gives a specification of materials used for the purpose of producing the examined cast iron, and Table 4 – chemical compositions of the resulting cast iron.

Table 1.
Chemical composition of cerium mixture

Chemical composition, %							
Si	Al	Mg	Ce	Nd	Pr	La	Fe
0.20	0.05	0.20	49.2	17.5	5.4	23.7	0.05

Table 2.
Chemical composition of ferrosilicon

Chemical composition, %						
Si	C	Mn	P	S	Al	Ca
67.1	0.27	0.42	0.038	0.004	2.05	2.40

Table 3.
Specification of materials used for the production and the treatment of aluminium cast iron

Designation of melt	Quantity, g				
	Basic charge materials			Materials used for cast iron treatment	
	Charge cast iron	Ferrosilicon (75wt% Si)	Aluminium A1	Cerium mixture	Ferrosilicon (75wt% Si)
I	1500	75	126	1.87	21.90
II	1500	75	135	1.88	22.11
III	1500	75	145	1.89	22.20
IV	1500	82	126	1.88	22.00
V	1500	82	135	1.89	22.10
VI	1500	82	145	1.90	22.30

Table 4.
Chemical composition of cast iron from the experimental melts

Designation of melt	Chemical composition, %						S_c*
	Al	C	Si	Mn	S	P	
I	5.64	2.68	4.50	0.12	0.010	0.040	1.63
II	5.13	2.87	4.98	0.13	0.016	0.030	1.78
III	6.02	2.48	4.97	0.14	0.014	0.040	1.75
IV	5.18	2.44	5.24	0.14	0.013	0.030	1.60
V	5.30	2.61	5.28	0.12	0.010	0.040	1.76
VI	5.35	2.41	5.30	0.13	0.012	0.035	1.64

*Sc-the eutectic saturation degree of the alloy

$$S_c = \frac{C_c}{4{,}25 - 0{,}3Si - 0{,}33P + 0{,}027Mn - 0{,}40S - 0{,}22Al}$$

where: C_c – total amount of carbon in cast iron, %
Si, P, Mn, etc.– total amount of Si, P, Mn, etc. in cast iron, %

Chemical composition of cast iron was determined by the analysis of shavings taken from the sinkheads of the cast rod specimens. The content of five basic elements and of aluminium was found by the conventional wet analysis.

Table 5.
Percentages of pearlite and ferrite along with the characteristics of graphite occurring in the examined cast iron

Designation of melt	Area of micro-section (%) occupied by pearlite and ferrite in the observation field*	Features of graphite determined within the observation field**
I	P 6 / Fe 94	80% III 7 + 20% VI/V 7
II	P 6 / Fe 94	75% III 6 + 25% VI/V 7
III	P 6 / Fe 94	60% III 6 + 40% VI/V 7
IV	P0 / Fe	50% III 6/7 + 50% VI/V 7
V	P0 / Fe	60% VI/V 6 + 40% III 6
VI	P0 / Fe	70% VI/V 6 + 30% III 6

*examinations held according to the Polish Standard PN-75/H-04661: *Grey cast iron, nodular cast iron and malleable. Metallographic examinations. Determining of microstructure*
** examinations held according to the Standard PN-EN ISO 945-1:2009: *Microstructure of cast irons - Part 1: Graphite classification by visual analysis*

Table 5 gives percentages of pearlite and ferrite along with the characteristics of graphite precipitates in the examined cast iron.

Beside the metallographic examinations done by means of the optical microscope (Table 5), there were also held some measurements using the NIS-Elements D program in order to characterise the achieved graphite precipitates. They included the determination of:

- the percentage of the area occupied by graphite (graphite fraction) – G_w ,%;
- perimeters of graphite precipitates per unit area – P, mm/mm^2;
- quantity of graphite precipitates per unit area – N, mm^{-2}.

Due to the fact that the graphite in the examined cast iron occurred in the form of isolated precipitates, it was also possible to determine their average diameter $\bar{d}$, calculated from the formula [21]:

$$\bar{d} = \frac{P}{\pi N}$$

where: $\bar{d}$ – the average diameter of isolated precipitates, mm;
P – the average perimeter of isolated precipitates per unit area, mm/mm^2;
N – the average number of isolated precipitates per unit area, mm^{-2}.

The results of examinations concerning graphite precipitates, including their assignment to the one of the four ranges of the shape factor ζ, are gathered in Table 6. The shape factor of graphite precipitates was calculated as a proportion of the area (A_i) to the squared perimeter (φ_i) of the *i*-th precipitate.

Figures 1-12 show successively graphite precipitates and microstructures of cast iron coming from each of the experimental melts.

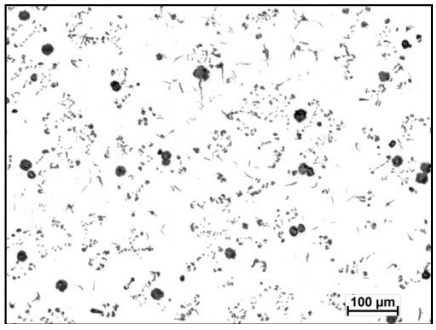

Fig. 1. Graphite precipitates in cast iron containing 5.64% Al and 4.50% Si (melt I), non-etched micro-section, magn. 100×

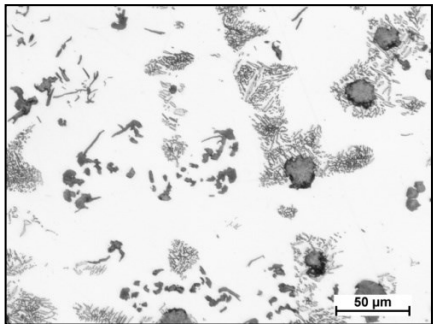

Fig. 2. The microstructure of cast iron containing 5.64% Al and 4.50% Si (melt I), etched micro-section, magn. 300×

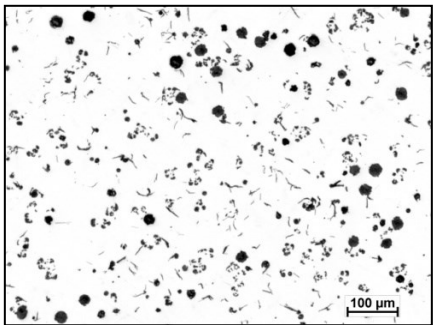

Fig. 3. Graphite precipitates in cast iron containing 5.13% Al and 4.98% Si (melt II), non-etched micro-section, magn. 100×

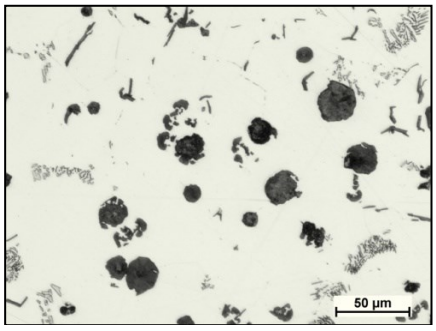

Fig. 4. The microstructure of cast iron containing 5.13% Al and 4.98% Si (melt II), etched micro-section, magn. 300×

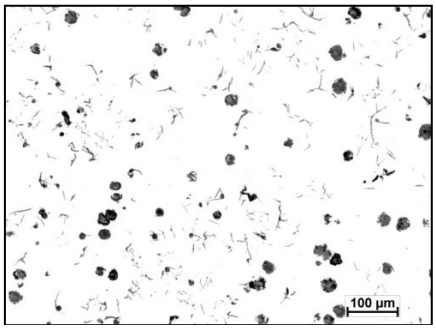

Fig. 5. Graphite precipitates in cast iron containing 6.02% Al and 4.97% Si (melt III), non-etched micro-section, magn. 100×

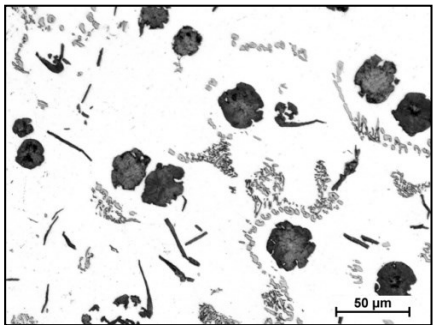

Fig. 6. The microstructure of cast iron containing 6.02% Al and 4.97% Si (melt III), etched micro-section, magn. 300×

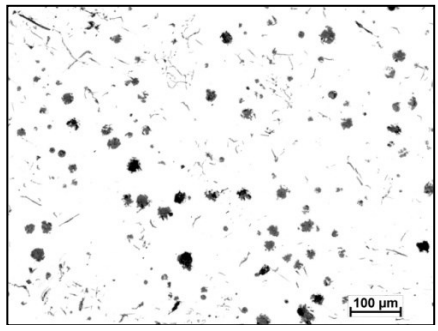

Fig. 7. Graphite precipitates in cast iron containing 5.18% Al and 5.24% Si (melt IV), non-etched micro-section, magn. 100×

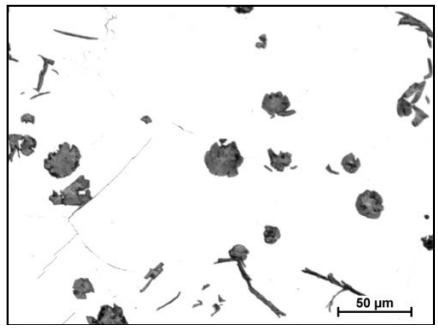

Fig. 8. The microstructure of cast iron containing 5.18% Al and 5.24% Si (melt IV), etched micro-section, magn. 300×

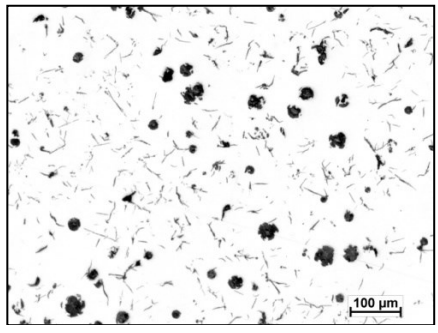

Fig. 9. Graphite precipitates in cast iron containing 5.30% Al and 5.28% Si (melt V), non-etched micro-section, magn. 100×

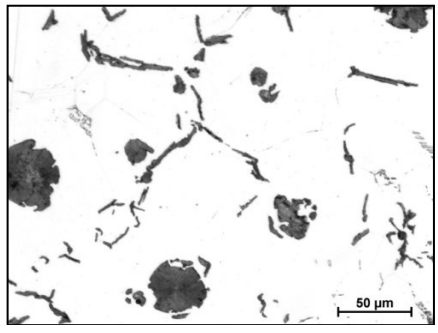

Fig. 10. The microstructure of cast iron containing 5.30% Al and 5.28% Si (melt V), etched micro-section, magn. 300×

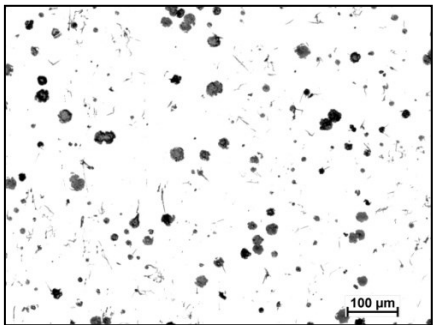

Fig. 11. Graphite precipitates in cast iron containing 5.35% Al and 5.30% Si (melt VI), non-etched micro-section, magn. 100×

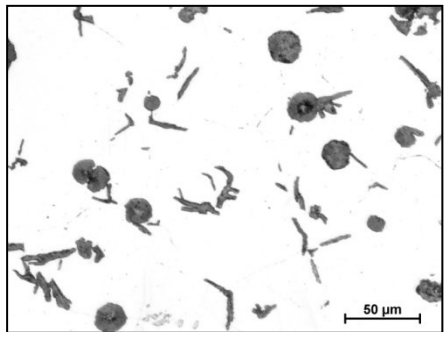

Fig. 12. The microstructure of cast iron containing 5.35% Al and 5.30% Si (melt VI), etched micro-section, magn. 300×

Table 6.
Characteristics of graphite precipitates occurring in the examined cast iron

Designation of melt	Content in cast iron, %		Average values in a specimen				Ranges of the shape factor ζ	Percentage within the individual ranges of the shape factor, %		
	Al	Si	G_w [%]	P [mm/mm^2]	N [1/mm^2]	$\bar{d}$ [µm]		Area of precipitates	Perimeter of precipitates	Number of precipitates
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*
I	5.64	4.50	13.38	65.11	1857	11.17	(0.00-0.02)	26.00	53.19	6.13
							<0.02-0.04)	42.05	33.06	23.49
							<0.04-0.06)	25.97	11.76	30.50
							<0.06-0.08)	5.98	2.00	39.88
II	5.13	4.98	14.54	57.90	1723	10.70	(0.00-0.02)	28.92	51.68	7.20
							<0.02-0.04)	37.97	32.90	21.05
							<0.04-0.06)	26.04	12.76	24.33
							<0.06-0.08)	7.07	2.65	47.41
III	6.02	4.97	8.31	40.39	1211	10.62	(0.00-0.02)	21.69	73.17	11.57
							<0.02-0.04)	27.80	13.88	35.13
							<0.04-0.06)	28.15	8.10	28.78
							<0.06-0.08)	22.37	4.86	24.52
IV	5.18	5.24	7.58	37.17	1101	10.75	(0.00-0.02)	12.57	30.85	8.12
							<0.02-0.04)	38.68	40.69	22.92
							<0.04-0.06)	34.03	21.76	31.69
							<0.06-0.08)	14.72	6.70	37.27
V	5.30	5.28	11.36	52.58	1484	11.28	(0.00-0.02)	28.57	52.94	13.89
							<0.02-0.04)	42.11	34.00	31.79
							<0.04-0.06)	34.03	21.76	31.69
							<0.06-0.08)	14.72	6.70	37.27
VI	5.35	5.30	7.94	28.88	965	9.54	(0.00-0.02)	4.45	54.07	3.83
							<0.02-0.04)	12.82	11.05	18.18
							<0.04-0.06)	31.52	15.66	26.85
							<0.06-0.08)	51.21	19.22	51.15

3. Conclusion

The analysis of data presented in Table 5, and also the Figs. 2, 4, and 6 indicate that small amounts of pearlite occurred in cast iron from the first three of the considered melts (I, II, III). The aluminium content in these alloys ranged from 5.1% to 6%, and the silicon content from 4.5% to 5% (see Table 4). An increase in silicon content by about 0.3% over the upper limit of the mentioned range combined with slightly reduced maximum aluminium content (to about 5.2÷5.3%) led to the occurrence of purely ferritic matrix (see data in Tables 4 and 5 and Figs. 8, 10, 12).

It should be noticed that only nodular and vermicular graphite was found in cast iron coming from all the examined melts (see data in Tables 5 and 6 and Figs. 1, 3, 5, 7, 9, 11). Neither flake graphite nor chunky graphite was observed. The area occupied by graphite precipitates in cast iron from all the melts ranged from about 8% to about 14%, the number of graphite precipitates per unit area from about 1000 mm^{-2} to about 1800 mm^{-2}, and the average diameter of precipitates fell within the range of 10÷11 μm.

The data from the columns 8 and 9 of the Table 6 allowed to determine the degree of graphite spheroidization η_{sf}, defined as the percentage of area occupied by graphite precipitates exhibiting the shape factor greater than 0.04 with regard to the total area of graphite precipitates. Its analysis shows that in the case of the material coming from the melts I, II, and III its value ranges from about 32% to about 51%. In the case of cast iron of slightly increased silicon content and slightly reduced aluminium content (melts IV, V, VI) the considered parameter is between the limits of about 49% and about 83%. The latter value was achieved in cast iron from the melt VI. The analysis of data from the columns 8 and 11 of Table 6 indicates that the number of graphite precipitates of the shape factor $\eta_{sf} > 0.04$ comprised from over 53% (cast iron from the melt III) to 78% (cast iron from the melt VI) of the total number of precipitates.

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