International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 4 Issue 07, July-2015

Ductile Cast Iron Induction Re-Melting

Dr. Olexiy A. Tchaykovsky,
Senior Professor,
Department of Foundry of ferrous and non-ferrous metals,
National Technical University of Ukraine "KPI"
Kyiv, Ukraine, Peremohy av., 37

Oksana V. Klok
Master student
Department of Foundry of ferrous and non-ferrous metals,
National Technical University of Ukraine "KPI"
Kyiv, Ukraine, Peremohy av., 37

***Abstract* — High impact and fatigue resistance of ductile cast iron compared to another types of cast iron is defined by the spherical shape of graphite inclusions. The sphericity of graphite gradually disappears after the exposure of the liquid cast iron in the ladle during casting. This process was previously investigated and the influencing factors such as magnesium content, exposure time and temperature were determined. The complete disappearance of the graphite sphericity was also observed after ductile cast iron re-melting. The aim of this work was to study the kinetics of graphite shape transformation from spherical to lamellar in ductile cast iron during the re-melting process. The effect of heat treatment exposure on the shape of graphite inclusions was determined.**

Keywords* — *Ductile cast iron; spherical graphite, modification, re-melting, residual magnesium content

I INTRODUCTION

1.1 Spherical graphite in ductile cast iron

There are many hypotheses regarding to the origin of spherical graphite in cast iron, but none of them provides a complex description of this process. The high temperatures complicate observations of a number of phenomena that could reveal the mechanism of spherical graphite formation during spheroidizing treatment and the role of magnesium and other spheroidizers in this process.

Kuznetsov et al. proposed the method, which allows to obtain the spherical shape of graphite in cast iron without adding of sphericity modifiers containing Mg, Se, Y and REM. Based on the final composition, treatment process parameters, the obtained ductile cast iron has following properties: $\sigma_в$=500…1000 MPa, δ=3…20%, HB = 169…350. Depending on the spheroidizing treatment and heat treatment regime, the structure of the metal matrix can be: ferritic (HB=60…235), ferritic-pearlitic (HB=220…270), pearlitic, bainitic and martensitic (HB=255…360). The average graphite size is 10...80 μm [1].

The principal industrial process of ductile cast iron production is based on using of spheriodizing elements. A range of properties of ductile cast iron is defined by graphite sphericity. In turn, the graphite sphericity entirely depends on the residual content of spheroidizer, mainly magnesium. Residual magnesium content, which gives the spherical graphite shape, depends on the cooling rate, modification process parameters and metal matrix structure. The amount of spheroidizer depends on many factors: the mass of cast iron which is processed, the mold filling time, casting wall thickness, sulfur content, temperature, cooling rate etc.

In case of insufficient quantities of spheroidizer and different cooling rates magnesium segregation occurs, causing lower magnesium concentration in the parts of the casting, which crystallize in the last turn. Microstructural and spectral analysis established the influence of different quantities of residual magnesium on the graphite shape in castings, cooled at the same rate.

Based on practice and the results obtained, it can be concluded that the residual magnesium content which ensure the correct spherical shape of graphite in castings with a wall thickness of 20...80 mm should not be lower than 0,041...0,042 %. Spheroidizing treatment technology of cast iron must guarantee satisfactory assimilation of magnesium in liquid metal.

According to Voloschenko et al. the residual magnesium content of castings, which crystallize with the formation of metastable structures should not be lower than 0,035 %. At lower magnesium content spherical graphite has irregular or mixed shape, which is unacceptable [2].

One of the main challenges of ductile cast iron production is to ensure a high graphite sphericity rate in castings obtained from modified cast iron. This problem particularly occurs due to prolonged filling of the molds and at low crystallization rates.

The effect of liquid ductile cast iron exposure on kinetics of graphite sphericity reduction is given in Table 1.1 [3]. In this study the initial cast iron with stable chemical composition was smelted in a furnace with basic lining at 1450...1470 °C and treated with optimal amounts of given modifiers. The modified cast iron was kept in the furnace at 1380...1420 °C and the liquid metal probes for analysis were taken every 3 min.

Based on the results given in Table 1.1 and Figure 1.1 it can be concluded that isothermal exposure of modified cast iron reduces the sphericity of graphite, but the intensity of this process depends on the modifier composition. Immediately after the spheroidizing treatment the sphericity rate was 83...93 %, after 10 and 20 min 70...88 % and 32...66 %, respectively.

(This work is licensed under a Creative Commons Attribution 4.0 International License.)

TABLE 1.1 - EFFECT OF DURATION OF EXPOSURE ON THE GRAPHITE SHAPE IN CAST IRON AFTER MODIFICATION

Modifier Composition		Graphite sphericity, % after exposure, min								
		0,5	*3*	*6*	*9*	*12*	*15*	*18*	*21*	*24*
1	Mg-Ni-Cu	88	88	85	80	65	55	35	35	-
2	Mg-Ni-REM	90	-	85	80	70	55	40	35	30
3	Mg-Si-Fe	90	-	80	75	60	45	-	30	-
4	Mg-Si-Fe-Ca	85	85	-	78	70	60	45	-	30
5	Mg-Ca-REM-Si-Fe	90	90	-	87	85	80	65	50	40
6	Mg-Ca-REM-Si-Fe	85	85	83	-	80	73	60	45	35
7	Mg-Ca-REM-Si-Fe-Ba	93	-	83	-	82	-	64	-	45

The lack of proportionality between the exposure duration of liquid modified cast iron and the graphite sphericity rate is typical for all investigated modifiers. The graphite sphericity reduction is slow for short durations of exposure and increases with time (Fig. 1.1).

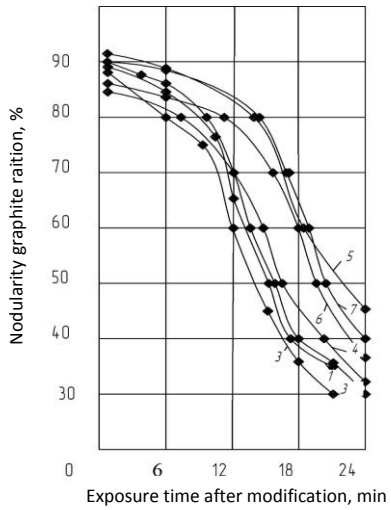

Fig. 1.1 Effect of exposure duration of liquid modified cast iron on graphite sphericity

Thus, in any case, the spheroidizing effect disappears and duration of exposure in liquid state is the key parameter of this process.

Therefore, the re-melting of ductile iron castings leads to complete disappearance of spherical graphite and further spheroidizing treatment required.

Special attention was dedicated to mechanism and kinetics of dissolution of spherical graphite at 700...1100 °C. It was established that the heating over the eutectoid transformation temperature significantly affects the spherical graphite dissolution kinetics. Lower overheating temperatures inhibit the carbon diffusion from graphite throughout the austenite to ferrite.

Carbon diffusion occurs directly in the ferrite grains as well as at the ferrite grain boundaries. The continuous transfer of carbon atoms to austenite creates the gap at the boundary between graphite and the metal matrix. Graphite dissolution in ferrite phase is uneven process and occurs with continuous acceleration. The carbon dissolution rate in austenite increases as the temperature increases. Graphite dissolves quickly at temperatures above 950 °C [4].

Thus, there are lots of studies dedicated to the influence of technological parameters on the shape of graphite in cast iron, however the comprehensive data regarding to the kinetics of graphite sphericity reduction are very limited.

The aim of this study is to fill the existing gap in literature and to investigate the graphite sphericity reduction during the re-melting of ductile cast iron.

2 EXPERIMENTAL METHODOLOGY

2.1. Cast iron smelting

Initial cast iron was smelted in coreless induction furnace IST-0.06 grade with crucible of 60 kg. Charge material was pig iron and steel scrap, chemical composition is shown in Table 2.1 and 2.2.

TABLE 2.1 - CHEMICAL COMPOSITION OF PIG IRON

Element	C	Si	Mn	S	P
Content, %	4,3	1,65	0,6	<0,03	<0,1

TABLE 2.2 - CHEMICAL COMPOSITION OF STEEL SCRAP

Element	C	Si	Mn	S	P
Content, %	0,03	0,3	0,06	0,01	0,1

The temperature of cast iron in the ladle before casting was measured with tungsten-rhenium thermocouple VR5/20. Spheroidizing treatment was performed in 10 kg ladle using complex modifier FeSiMg-7, the chemical composition is shown in Table 2.3.

TABLE 2.3 – CHEMICAL COMPOSITION OFFESIMG-7

Element	Mg	Ca	REM	Si	Al	Fe
Content, %	6,5…8,5	0,2…1,0	0,3…1,0	45…55	≤1,2	other

The amount of modifier was 2% of metal weight. Cast iron temperature before modification was 1400...1420 °C.

2.2. Sample preparation

The initial casting with 12 samples (Fig. 2.1) was produced in dry sand mold.

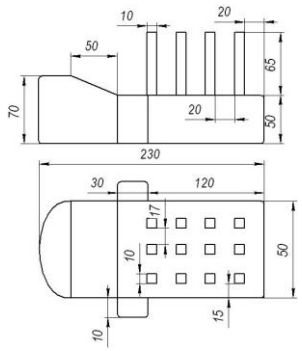

Fig. 2.1 Casting with samples

Samples were cut from the casting and the central part of 10×10×35mm was cut from the each sample.

2.3 Metallographic analysis

The structure of the metal matrix, graphite nodularity rate (GNR) [3], the amount and average size of graphite inclusions were defined by means of light optical microscopy (LOM).

(This work is licensed under a Creative Commons Attribution 4.0 International License.)

3 EXPERIMENT

3.1 *Induction heating and melting of cast iron with nodular graphite.*

The experimental setup is shown on Figure 3.1. Ductile cast iron sample was partially placed in inductor and the other part was intensively cooled with water.

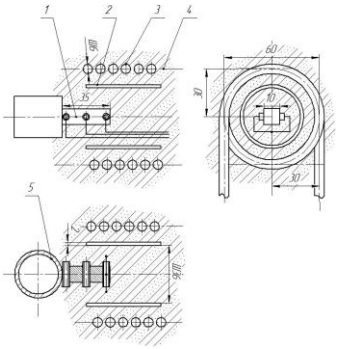

Fig. 3.1 Scheme of the experimental setup: 1-sample; 2-steel tube; 3-inductor; 4-sand, 5-vessel filled with water

Three thermocouples were inserted in the holes at 5, 12 and 30 mm from the sample edge. The inductor was filled with sand.

One part of the sample was heated to 1260...1300 °C, the middle part – to 1250...1280 °C, and the other part – below eutectic temperatures – 1110...1160 °C (Fig. 3.2). Samples were exposed for 4, 8, 16 and 20 min and cooled down at room temperatures.

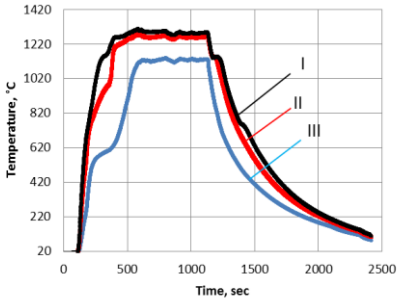

Fig. 3.2 Heating and cooling curves for thermocouples: I – 30 mm from the sample edge, II – 12 mm, III – 5 mm

The longitudinal sample cross-sections were taken for microstructure analysis.

3.2 *Effect of exposure time on graphite shape and size*

It was observed that all samples microstructures can be characterized by three zones (Fig. 3.3):

- zone with interdendritic dot graphite (part of the sample overheated above the melting point);
- transition zone (between melted and solid phase);
- spherical graphite zone (forcibly cooled part).

The metallographic analysis results are listed in Table 3.1.

TABLE 3.1 - RESULTS OF METALLOGRAPHIC ANALYSIS

Exposure time, min	Average graphite size, μm	Graphite sphericity rate, %	Average graphite amount,%
initial	8	94…96	12,3
4	7	94…96	11.7
8	6	90…92	10,1
16	8	95…97	12,2
20	6	96…98	12,1

According to the results of metallographic analysis it was found that the average graphite size, sphericity rate and the amount of graphite inclusions in forcibly cooled part of the sample has not changed compared to the initial ductile cast iron. However, the initial perlite (45)/ferrite (55) metal matrix structure has changed to perlite (70)/ferrite (30).

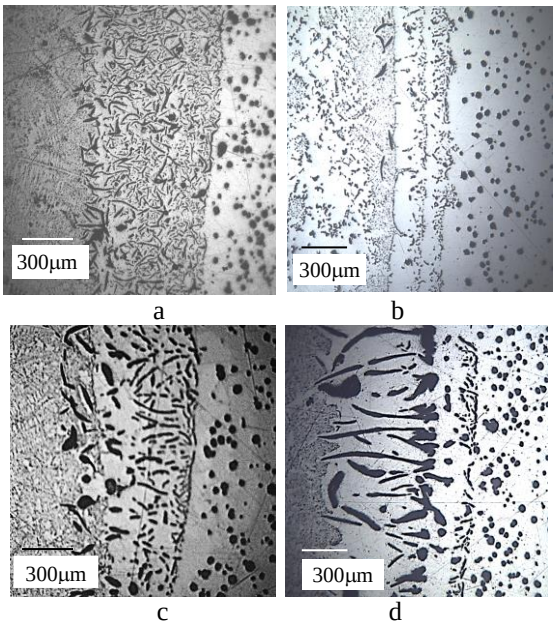

Fig.3.3 Microstructure of ductile cast iron exposed for: a) 4 min, b) 8 min, c) 16 min, d) 20 min.

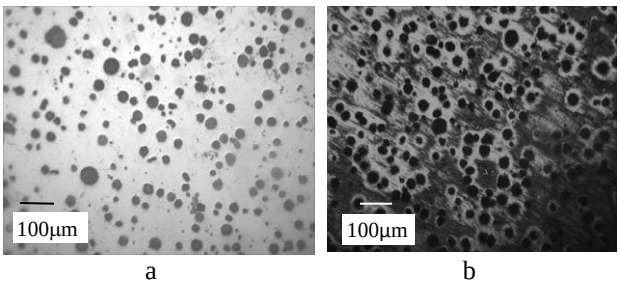

Fig. 3.4 Microstructure of the initial ductile cast iron: a) without etching, b) after etching.

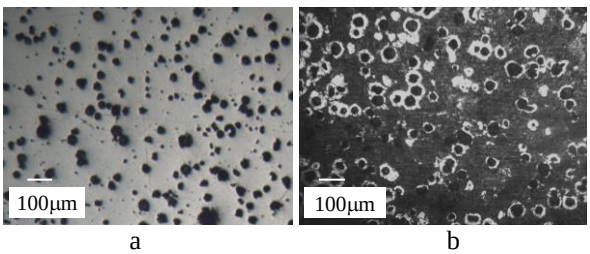

Fig. 3.5 Microstructure of forcibly cooled sample part: a) without etching, b) after etching

(This work is licensed under a Creative Commons Attribution 4.0 International License.)

The structure of the transition zone for nearly all samples has shown the exfoliation into six specific sub-zones (Fig. 3.3, Fig. 3.6):

- I – the subzone of large flake graphite partially situated in ledeburite;
- II – depleted carbon subzone with almost no graphite;
- III – the subzone with small flake and vermicular graphite;
- IV – depleted carbon subzone;
  V – the subzone with flake and vermicular graphite;
- VI – carbon depleted subzone bordering the zone with spheroidal graphite (part of the sample, which was forcibly cooled).

Etching of samples has shown ferrite and pearlite microstructure of the transition zone. Ferrite islands around graphite inclusions indicate that they were formed from the initial spherical graphite.

Partially whited structure with cementite in form of ledeburite was observed in overheated parts of all samples. Sample, exposed for 4 min has shown ledeburite with perlite and the shunky graphite, surrounded by ferrite. All other samples have clear ledeburite with interdendritic dot graphite.

In order to determine the width of the transition zone 10 measurements were made for each sample. According to the results of measurements the following was established (tab. 3.2):

- the transition zone of the sample exposed for 4 min varies from 502 to 523 μm (average - 513.7 μm);
- the transition zone of the sample exposed for 8 min varies from 223 to 256 μm (average - 241.6 μm);
- the transition zone of the sample exposed for 16 min varies from 534 to 555 μm (average - 542.8 μm);
- the transition zone of the sample exposed for 20 min varies from 615 to 642 μm (average - 630.8 μm).

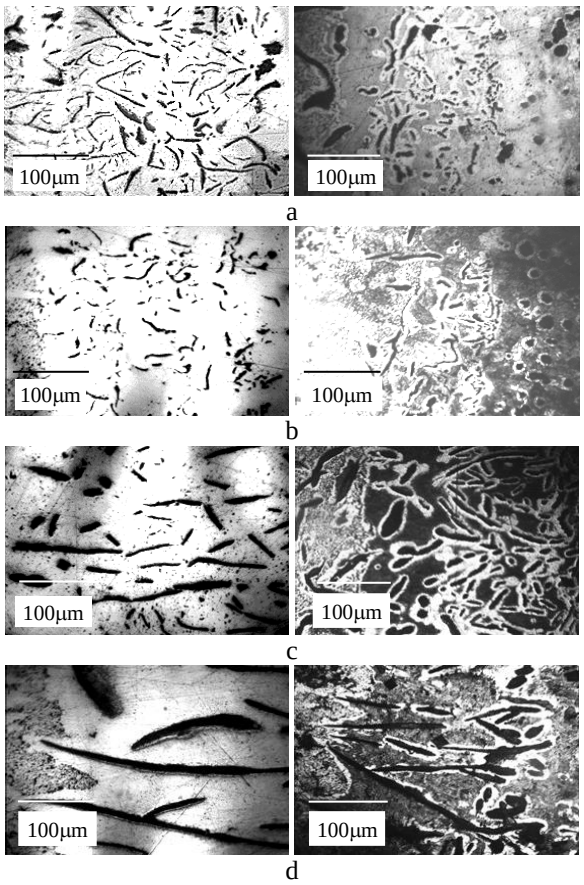

Fig. 3.6 - Structure of the samples between molten and solid zones after exposure time: a) 4 min, b) 8 min, c) 16 min, d) 20 min

TABLE 3.2 CHARACTERISTICS OF THE TRANSITION ZONE WIDTH

Exposure, min	The transition zone width, μm									
	View sight									
	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
4	512	519	506	522	512	502	510	523	513	518
8	250	224	246	225	253	221	245	223	260	256
16	534	555	543	547	542	538	551	541	537	540
20	634	628	629	642	641	635	627	615	632	625

TABLE 3.2A CHARACTERISTICS OF THE TRANSITION ZONE WIDTH

Exposure min	Average width, μm
4	513,7
8	241,6
16	542,8
20	630,8

(This work is licensed under a Creative Commons Attribution 4.0 International License.)

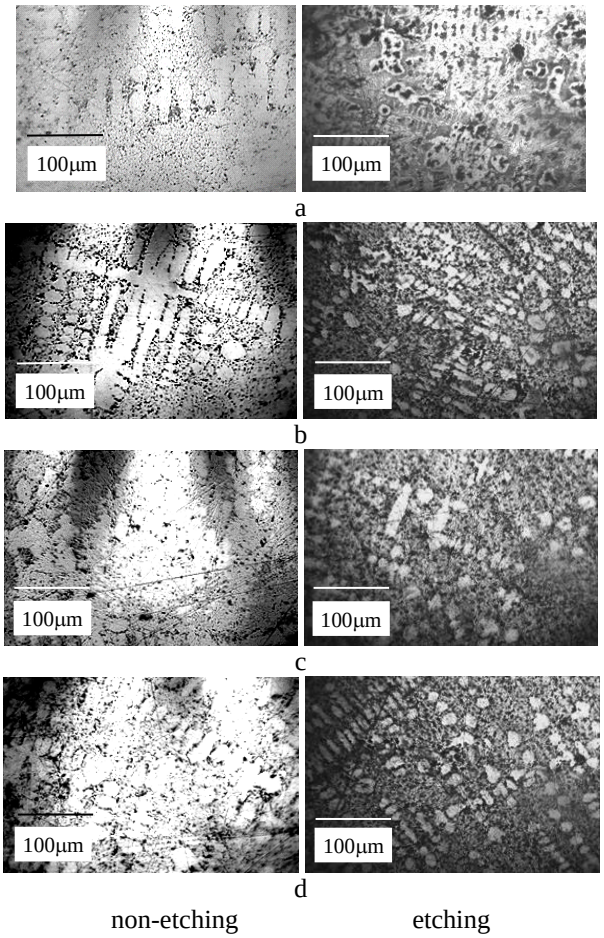

Fig.3.7 Microstructure of the melted sample part exposed for: a) 4 min, b) 8 min, c) 16 min, d) 20 min

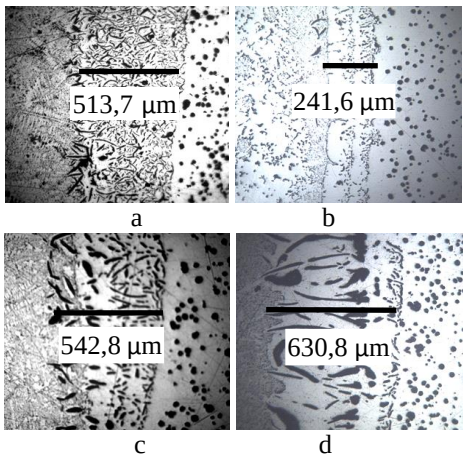

Fig. 3.8 Transition zones of samples exposed for: a) 4 min, b) 8 min, c) 16 min, d) 20 min

TABLE 3.3 DIMENSIONS OF TRANSITION ZONE SUBZONES

Ezposure, min	Subzone width, µm					
	I	*II*	*III*	*IV*	*V*	*VI*
4	153	61	300	23	252	64
8	225	112	82	53	99	87
16	319	45	125	23	115	59
20	620	56	47	57	103	43

Based on the metallographic analysis it was found that subzone I width varies from 153...620 µm, II – 45...112 µm, III – 47 ...300 µm, IV – 23...27 µm, V – 99...252 µm and VI – 43...87 µm.

It was also observed that the average graphite length for subzone I varies between 73...250 µm, for III - 62...112 µm, V – 34...87 µm. In subzones II, IV and VI graphite is practically absent (Table 3.4, Fig 3.10).

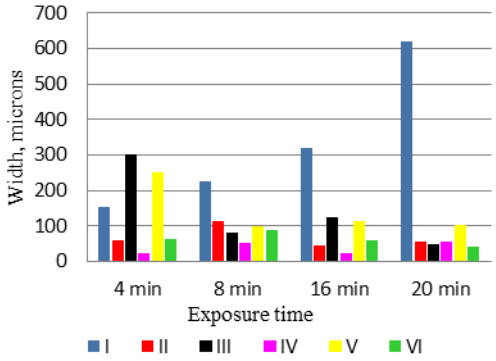

Fig. 3.9 Effect of exposure time on the widths of transition zone subzones

TABLE 3.4 GRAPHITE LENGTHS IN THE TRANSITION ZONE SUBZONES

Excerpt time, min	Graphite length microns					
	I	*II*	*III*	*IV*	*V*	*VI*
4	92	-	62	-	34	-
8	73	-	52	-	27	-
16	120	-	112	-	86	-
20	250	-	70	-	87	-

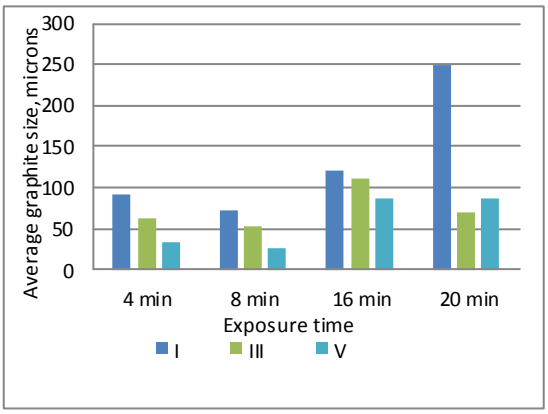

Fig. 3.10 Average graphite size in the transition zone subzones

Figures 3.11 and 3.12 show the impact of exposure time on the width of transition zone and graphite size, respectively.

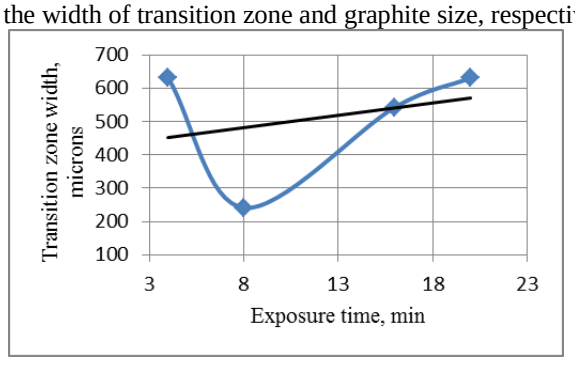

Fig. 3.11 Effect of exposure time on the transition zone width

(This work is licensed under a Creative Commons Attribution 4.0 International License.)

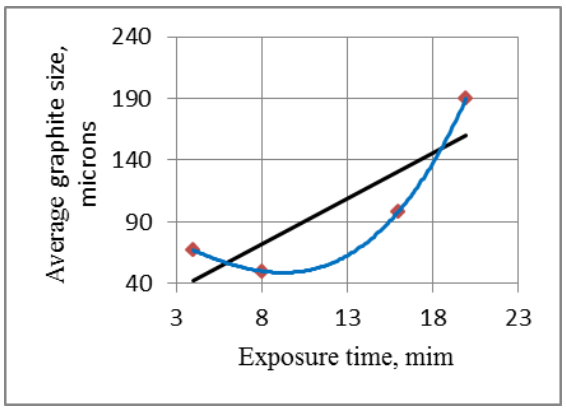

Fig. 3.12 Effect of exposure time on the average graphite size

4 CONCLUSIONS

All ductile cast iron samples subjected to the heat treatment had shown three main zones with respect to the graphite shape: a zone with spherical graphite, transition zone and zone with interdendritic dot graphite. The transition zone structure in almost all specimens can be divided into six subzones:

- I – the subzone of large flake graphite partially situated in ledeburite;
- II – depleted carbon subzone with almost no graphite;
- III – the subzone with small flake and vermicular graphite;
- IV – depleted carbon subzone;
- V – the subzone with flake and vermicular graphite;
- VI – carbon depleted subzone bordering the zone with spheroidal graphite (part of the sample, which was forcibly cooled).

It was also found that decreasing of the heat treatment time from 20 to 8 min decreases the transition zone width from 630 μm to 250 μm and graphite size from 98 μm to 50 μm, respectively. Graphite inclusions, surrounded by ferrite islands in the transition zone indicate their initial formation of spherical graphite.

Considering the processes, which occur at different durations of the heat treatment as parts of the one process, the following kinetics of graphite shape transformation can be suggested. The collapse of spheroidal graphite and flake graphite formation between the heated and cooled parts of the specimen occurs due to the evaporation of residual magnesium at high temperatures. Further increasing of exposure time creates conditions for more complete diffusion of silicon and carbon, which leads to exfoliation of transition zone into the subzones with different carbon content.

The smooth transformation from spheroidal to flake graphite was not observed at given experimental conditions.

REFERENCES

[1] Kuznetsov B.L. Nodular and vermicular iron production without spheroidizing modifiers. // Foundry. Manuf. - 1985. - № 8. - S. 18-19..
[2] Voloschenko M.V., Toropov A.I., Influence of residual magnesium on the graphite shape. // Foundry. Manuf. - 1961. - № 5. - S. 30..
[3] Litovka V.I. Improving the quality of ductile iron castings. Kiev, Naukova Dumka, 1987. -260 p..
[4] Yakovlev F.I, About the mechanism of dissolution of graphite during induction heating of the nodular iron casts. // Foundry. Manuf. - 1978. - № 3. - S. 3-5..

(This work is licensed under a Creative Commons Attribution 4.0 International License.)