Arc Re-Melting of Ductile Cast Iron after Fesimg Modification

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***Abstract* — 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 in ductile iron treated with FeSiMg-7 alloy during the arc re-melting process. The effect of heat treatment exposure on the shape of graphite inclusions was determined.**

Keywords* — *Ductile Iron; Spherical Graphite, Modification, Re-Melting, Graphite Nodularity Degree, Graphite Shape, Nodular Graphite Treatment, Exposure Time, Cooling Speed

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.

The principal industrial process of ductile cast iron production is base on using of spheroidizing elements. A range of properties of ductile cast iron is define 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.

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 [1].

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 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.

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).

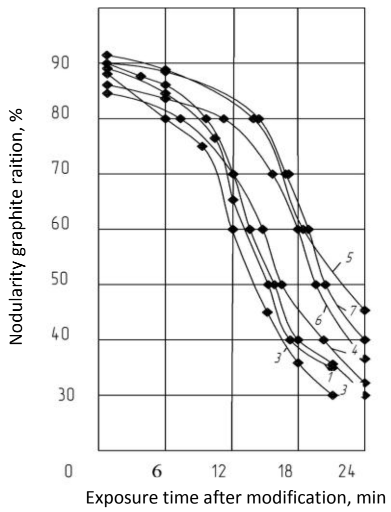

Fig. 1.1 Effect of exposure duration of liquid modified cast iron on graphite sphericity

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 [2].

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

The use of mischmetal (consisting of cerium) gives positive results of graphite spheroidizing.

Research and industrial tests mischmetal used for processing nickel-carbon and iron-carbon alloys have shown that spherical graphite formed at high cooling rates and low sulfur content [3].

Research on re-melting samples of nickel-carbon alloy, pre-treated by spheroidizing elements, showed that the most effective cerium [3, 4].

The base alloy had included mostly spherical graphite shape (fig1.2) [3]. After re-melting and cooling of samples at a speed of 20 degrees per minute spherical graphite disappears, as in the samples that were modified magnesium, and the samples that have been modified cerium (fig.1.3) [3].

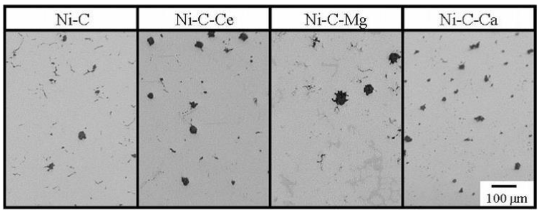

Fig 1.2 Graphite inclusions in base alloy specimens

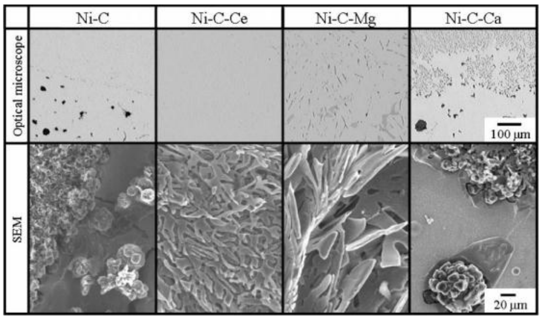

Fig 1.3 Graphite inclusions in specimens cooled at a speed 20 degrees/min under argon and hydrogen.

After re-melting and cooling of samples at a speed of 40 degrees per minute spherical graphite is stored only in the samples that were modified cerium. In the samples that have been modified magnesium graphite spherical shape completely lost (fig.1.4).

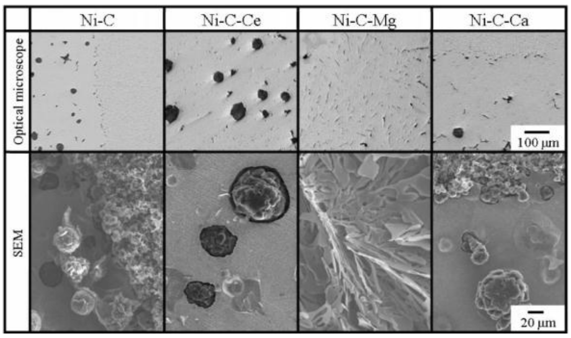

Fig 1.4 Graphite inclusions in specimens cooled at a speed 40 degrees/min under argon and hydrogen.

So, nodularizasion graphite effect disappears in the samples that were modified magnesium and re-melting at temperature of 1400 °C and exposure in to liquid 10 minutes. Increasing the cooling rate from 20 to 40 deg/min does not affect the shape of graphite inclusions.

The aim of this study is to fill the existing gap in literature and to investigate the graphite sphericity reduction during the arc re-melting of ductile cast iron modified with FeSiMg-7.

2 EXPERIMENTAL METHODOLOGY

2.1. Cast iron smelting

Base cast iron was melted in core-less induction furnace with acidic lining crucible, containing 60 kg. The charge consists of pig iron and steel scrap. The chemical composition of pig iron is given in table 2.1.

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

For the cast iron spheroidizing treatment used FeSiMg-7 alloy. FeSiMg-7 chemical composition is given in Table 2.3.

Cast iron temperature before pouring into molds was measured tungsten- rhenium thermocouple VR5/20 paired with a digital potentiometer A565.

TABLE 2.3 – CHEMICAL COMPOSITION OF FESIMG-7

Element	Mg	Si	Ca	REM	Al	Fe
Content, %	6.5…7.5	50…55	0,2..1	0,3…1	1,2	rest

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

For cast iron treatment and molds pouring was used lade with volume of 10 kg. After filling, the molds cool to room temperature.

2.2. *Sample preparation*

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

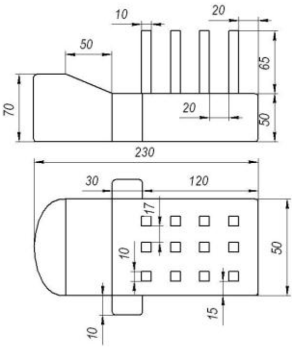

Fig. 2.1 Casting with samples

The molten and superheated to the temperatures 1450 °C cast iron was treated with mischmetal FeCeMg-5 in the amount of 3% by weight of metal. The molds were poured with modified cast iron, and cooled to room temperature

In each ductile iron sample with the sizes of 70 × 10 × 10 mm three through holes with diameter 3 mm were made (Fig. 2.2).

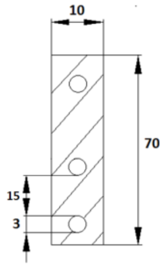

Fig 2.2 Research sample scheme

Two holes required for installation of thermocouples, and the third (lower) to supply contact.

Sample was molded in mold-box with diameter of 200 mm and a height of 300 mm. Schematic diagram of the experimental mold is shown in Fig. 2.3.

Thermocouples 3, 4 is set in the holes for temperature recording at two points during the sample heating and melting of the. Thermocouple 3 was set at the upper part of the sample, where the heating and melting occur, for control the desired temperature. Thermocouple 4 was installed at the bottom of the sample, is designed to control temperature of solid iron.

Melting was conducted with carbon electrode. The temperature was kept in two ranges 1350 °C…1380 °C and 1050 °C…1100 °C during a specified time.

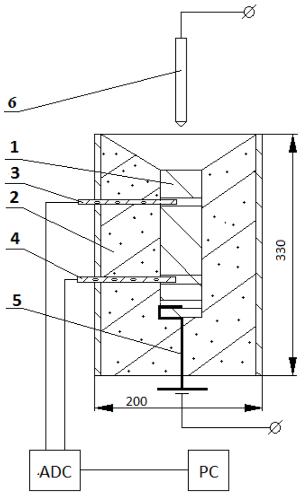

Fig 2.3 Schematic diagram of the experimental mold: 1 – sample; 2 – sand-clay mixture; 3 – thermocouple 1; 4 – thermocouple 2; 5 – contact; 6 – carbon electrode

After re-melting and exposure sample cooled in mold to room temperature.

The sample was purified by residues of molding mixture and polished for metallographic research.

2.3 Metallographic analysis

Determination of graphite nodularity degree (GND) conducted by the method, developed IPL of Academy of Sciences of Ukraine. To determine the amount of graphite inclusions in cast iron used Hlaholeva point method.

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).

3 EXPERIMENT

3.*1 Nodular iron samples structure characteristics after FeSiMg-7alloy modification.*

For research were produced samples with 70 mm length and a 10 mm width (a square cross-section). Cast iron was treated with FeSiMg-7 alloy and pureed into dry sand mold. After samples separation the high-temperature annealing was carried out at a temperature 960...980 °C followed by cooling in the furnace.

The results of metallographic studies found, that graphite nodularity degree of base ductile iron modified with FeSiMg-7 alloy is 90...95 %, the average graphite size is in the range of 4...8 μm and the graphite inclusions quantity is in the range 250...300 pcs/mm^2 (fig. 3.1, a).

Graphite inclusion features of base ductile iron and metal matrix structure shown in the table 3.1.

TABLE 3.1 – CHARACTERISTICS OF THE BASE NODULAR IRON STRUCTURE AFTER TREATMENT WITH FESIMG-7 ALLOY AND HIGH-TEMPERATURE ANNEALING.

Indicator	Value
Graphite inclusion size, μm	4…8
Graphite inclusion quantity, pcs/mm^2	250…300
Graphite nodularity degree, %	90…95
Ferrite/Perlite quantity, %	35/65

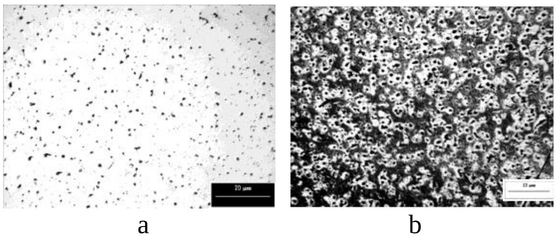
a
b

Fig. 3.1 Structure of base nodular iron modified with FeSiMg-7 alloy. a – not etched; b – etched

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

3.2 Graphite inclusions characteristics after nodular iron re-melting

3.2.1 Re-melting ductile iron modified with FeSiMg-7alloy at high temperature and short-term exposure conditions.

The sample was re-melted by carbon electrode electric arc. Graph of heating, exposure and cooling mode are presented in fig. 3.2. Samples from nodular iron heated to a temperature 1350...1380 °C and exposure during 25...30 seconds.

The total time during which part of the sample was in liquid state is 55-50 seconds. After heating, melting, exposure, and cooling the characteristics of graphite inclusions in the sample part, that was re-melted, were investigated. Metallographic analysis conducted by 3 mm – in direction from temperature control point to melting bath (fig.3.3).

In general, the graphite inclusions changed shape from nodular to fully lamellar (fig. 3.3). In solid part, close to the limit melting, graphite has a nodular shape. Dimensions of inclusions are in the range 3…5 μm, the amount of graphite inclusions is in range from 200 to 250 pcs/mm^2 and the nodularity (GND) is 90-95 %.

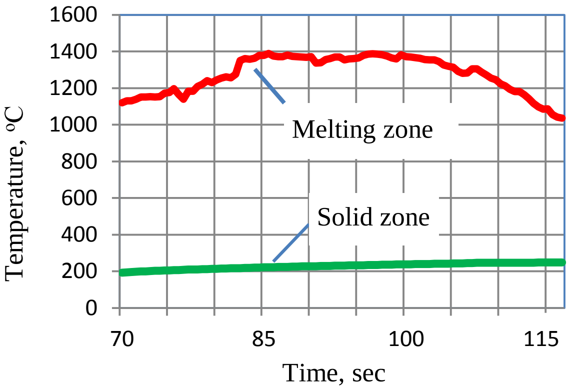

Fig 3.2 Graph of ductile iron high temperature heating and short term exposure mode

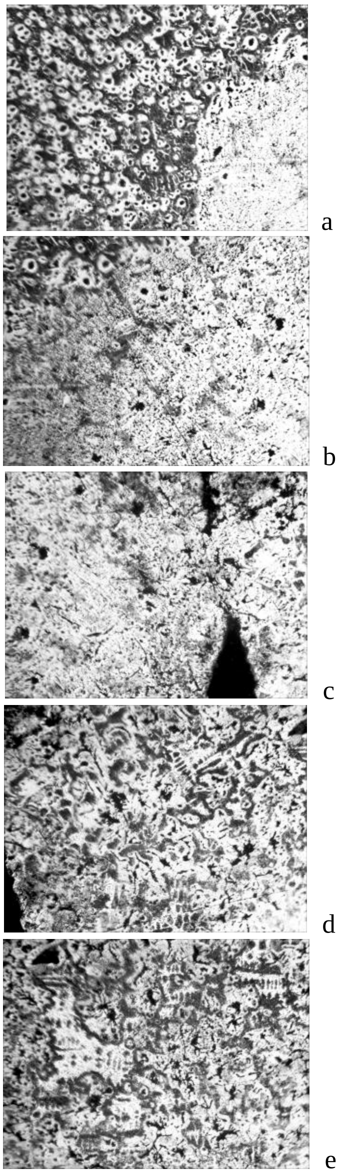

Fig 3.3 Graphite inclusions on the sample length after re-melting at the temperature 1350...1380 °C and exposure time 25...30 seconds: a - 0 mm (base ductile iron); b - 3 mm; c - 6 mm; d -9 mm; e - 12 mm.

In the transition area (fig. 3.4) observed partially shanky graphite with sizes 1...4 μm. In part of the sample, which is liquid, spherical graphite inclusions are absent. In the melting area was found partially turbulence graphite with length 3…4 μm, coral graphite with length 3…5 μm, lamellar graphite with length 10…200 μm. Features graphite particles are shown in table 3.2.

Metal matrix structure along the length of the sample changes from ferrite-pearlite, in solid part to cementite and ledeburite in apart, which was re-melted.

TABLE 3.2 – GRAPHITE INCLUSIONS CHARACTERISTICS IN THE RE-MELTED SAMPLE AREA OF DUCTILE IRON MODIFIED WITH FESIMG-7 ALLOY.

Distance, mm	Graphite shape	Inclusion dimension, μm	GND, %	Average graphite amount, %
Initial (0)	Nodular	3...5	90...95	200...250
2	coral	1...2	0	100...150
4	Lamellar, partially turbulence	1,5...6	0	100...150
6	Lamellar, partially turbulence, coral	2,5...12	0	150...200
8	Lamellar, partially turbulence, coral	10...100	0	150...200

Along the entire melting line in solid part of ductile iron sample local concentrations of coral and broken graphite inclusions with length up to15 μm are present. These local concentrations were observed at the distance 16…600 μm from the melting boundary. At the same distance, spherical graphite inclusions are present (fig .3.5). Some of local concentrations broken and coral graphite inclusions, that are close to the melting boundary, having contact with the liquid phase (fig. 3.6). All other local concentrations of coral and broken graphite such contacts haven't. Non-nodular graphite local concentration effect near the melting zone showed at fig. 3.5.

Spherical graphite includes in ductile iron that was modified with FeCeMg-5 alloy during re-melting begin to lose spherical graphite shape in solid near melting boundary.

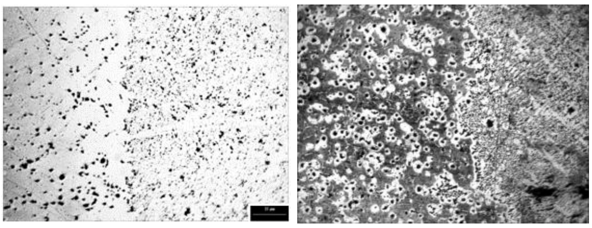
a b

Fig. 3.4 Melting zone of re-melted ductile iron modified with FeSiMg-7 alloy. a – not etched; b – etched

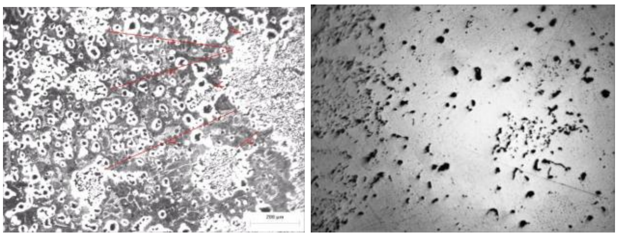
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Fig. 3.5 The local concentrations of non-nodular graphite in ductile iron modified with FeSiMg-7 alloy after re-melting at the temperature 1350…1380 °C and exposure during 25…30 sec. a – etched; b –not etched.

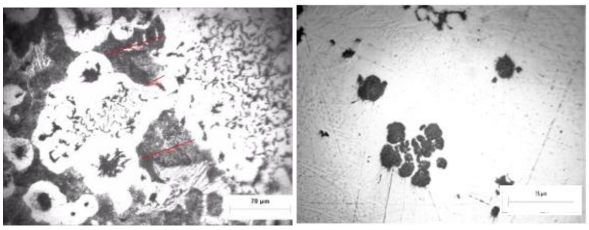
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Fig. 3.6 Enlarge local concentration, connected with melting area, of non-nodular graphite in ductile iron modified with FeSiMg-7 alloy after re-melting at the temperature 1350…1380 °C and exposure during 25…30 sec. a – etched; b – not etched.

The width of the transition zone or melting zone is in the range 30…75 μm (fig. 3.7).

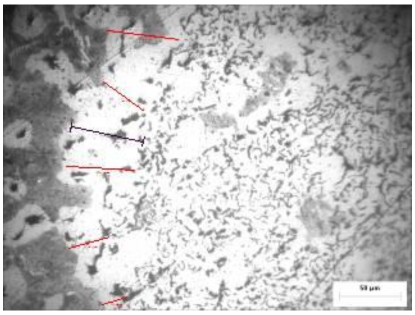

Fig. 3.7 The transition (melting) zone of ductile iron modified with FeSiMg-7 alloy after re-melting at the temperature 1350…1380 °C and exposure during 25…30 sec (etched).

3.2.2 Re-melting ductile iron modified FeSiMg-7alloy at low temperature and long term conditions.

Sample modified with FeSiMg-7 alloy, was heated to the temperature.1050...1100 °C (near magnesium boiling point) and exposure during 7 min 10 second (fig. 3.8).

Metallographic analysis showed that after nodular iron heating and exposure at 1050...1100 °C, during 7 minutes 10 seconds, in the area of the sample that has been re-melted, there were no changes in the shape of graphite inclusions (fig. 3.9).

After heating, exposure, and cooling at different distances from the boundary of the heating occurs only changing the size and amount of graphite inclusions.

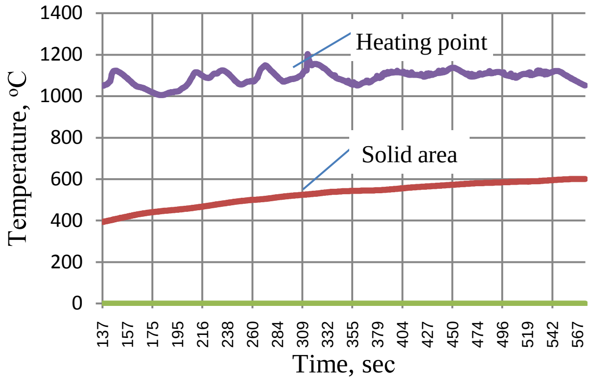

Fig. 3.8 Graph of ductile iron low temperature heating and long term exposure mode

Data on the graphite inclusions changing are shown in table 3.3.

As part of the sample, which had a temperature below 1050...1100 °C graphite inclusions have nodular shape. The nodular graphite inclusions diameter decreased to 4…6 µm. Graphite nodularity remained at the same level 90…95 %. Graphite inclusions amount decreased from 250 to 200 pcs/mm^2.

In the heated area, from the point of control to the heat source there is a general pattern of decline graphite sphericity to 75…85 %.

Graphite inclusions amount decreased to 180 pcs/mm^2. Present some graphite inclusion that have partially broken shape and their size are 1,5...3 µm. The amount of their graphite inclusions is 5...10 pcs/mm^2. (рис.3.16)

TABLE 3.3 – GRAPHITE INCLUSIONS CHARACTERISTICS IN THE RE-MELTED SAMPLE AREA OF DUCTILE IRON MODIFIED WITH FESIMG-7 ALLOY (EXPOSURE TEMPERATURE 1050...1100°C, TIME 7 MINUTES 10 SECONDS).

Distance, mm	Diameter, µm	GND, %	Average graphite amount,%
Initial (0)	4...6	90...95	200...250
3	1,5...4	80...90	150..200
6	1...3,5	80...85	150...180
9	1,5...3,5	75...85	150...180

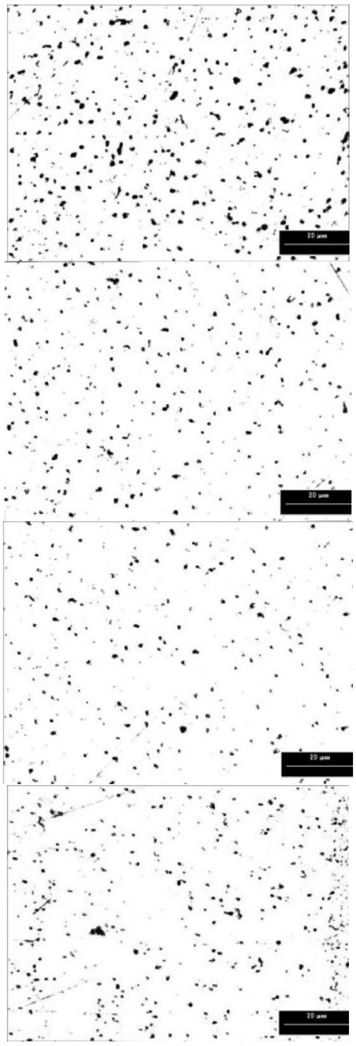

Fig. 3.9 Graphite inclusions in the ductile iron re-melted area (various view sight) at the temperature 1050...1100°C, at 0 mm, 3 mm, 6 mm and 9 mm, respectively

4 CONCLUSIONS

- At the repeated re-melting ductile iron modified with FeSiMg-7 alloy it is enough exposure at 25…30 sec in liquid state at temperature 1350…1380 °C for nodular graphite inclusions destruction. In the re-melted phase observed includes of coral, some turbulence and lamellar graphite. The size of these includes increase from 150 to 200 µm, in the direction from melting zone to the heat source.
- In the solid phase, directly in contact with the melting boundary, observed local concentrations with broken and coral graphite inclusions. These local concentrations are situated along melting boundary at the distance from 16 to 600 µm. Some of the local concentrations have contact with the liquid (re-melted) phase. But, most of the local concentrations separated from the liquid (re-melted) phase with solid ductile cast iron containing spheroidal graphite.
- Heated, nodular cast iron, modified with FeSiMg-7 alloy, up to magnesium boiling temperature 1050...1100°C, and exposure at 7 min and 10 sec there are no significant changes graphite inclusions. However revealed that toward the liquid phase reduced average graphite inclusions size from 5 to 3 µm, average graphite inclusions amount decreases from 300 to 180 pcs/mm^2 and nodularity decreases from 95 to 75 %.

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