Arc Re-Melting of Ductile Cast Iron After Mischmetal Fecemg 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 by mischmetal FeCeMg 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, Arc Re-Melting, Graphite Nodularity Degree, Graphite Shape, Nodular Graphite Mischmetal

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).

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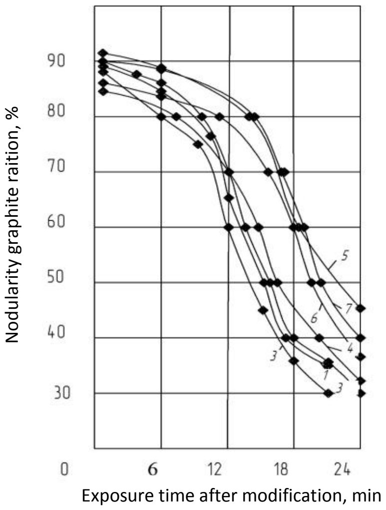

Fig. 1.1 Effect of exposure duration of liquid modified cast iron on graphite sphericity

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].

Repeated iron re-melting in argon at various cooling rates within 20-1000 degree/min, shown that nodular graphite keeps its shape for speed 40 degrees/min. At lower speeds spheroidal graphite disappears (fig1.2 and 1.3) [3].

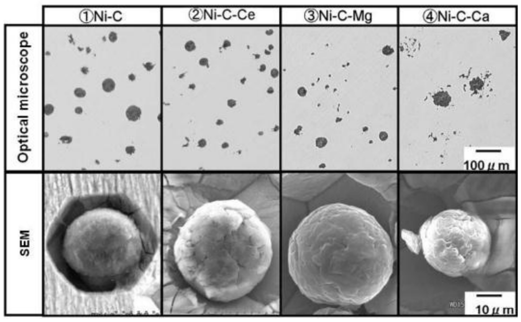

Fig 1.2 Graphite inclusions in specimens cooled at a speed 1000 degrees/min under argon and hydrogen.

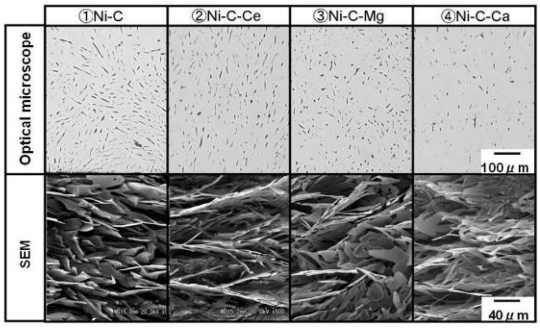

Fig 1.3 Graphite inclusions in specimens cooled at a speed 20 degrees/min under argon and hydrogen.

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 by mischmetal FeCeMg.

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 mischmetal FeCeMg-5. Mischmetal FeCeMg-5 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.

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TABLE 2.3 – CHEMICAL COMPOSITION OF MISCHMETAL FESCEMG-5

Element	Mg	Ce	La	Nd	Pr	Fe
Content, %	4…5	40…45	18…25	10…12	5…7	≤ 6

The amount of modifier was 3% 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.

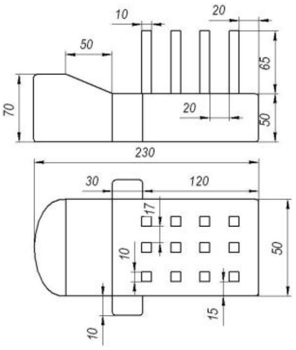

Fig. 2.1 Casting with samples

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).

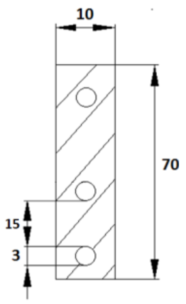

Fig 2.2 Research sample scheme

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. Determining the sample melting point occurs at 1130 °C, i.e. at a temperature slightly above the solidus. The temperature was kept in two ranges 1130 °C…1320 °C and 1050 °C…1100 °C during a specified time.

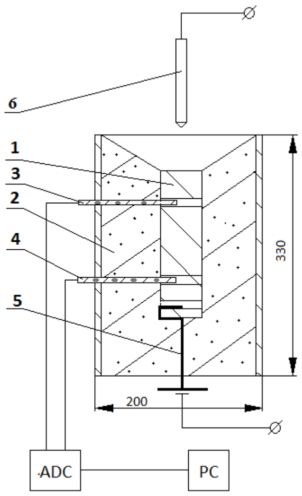

Fig 2.3 Schematic diagram of the experimental mold: 1 – sample; 2 – sand-clay mixture; 3 – thermocouple 1; 4 – thermocouple; 2 5 – contact; 6 – carbon electrode

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

The sample was purified by residues of molding mixture (fig. 2.4), and polished for metallographic research.

Fig 2.4 Samples after partial re-melting and holding for a specified time.

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 mischmetal FeCeMg-5 modification.

For research were produced samples with 70 mm length and a 10 mm width (a square cross-section). Cast iron was treated with mischmetal FeCeMg-5 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.

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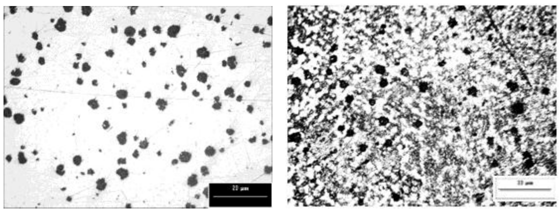
The results of metallographic studies found, that graphite nodularity degree of base ductile iron modified by mischmetal FeCeMg-5 is 90...95 %, the average graphite size is in the range of 3...7 μm and the graphite inclusions quantity is in the range 120...140 pcs/mm^2 (fig. 3.1, a).

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 AND HIGH-TEMPERATURE ANNEALING.

Indicator	Value
Graphite inclusion size, μm	3…7
Graphite inclusion quantity, pcs/mm^2	120…140
Graphite nodularity degree, %	90…95
Ferrite/Perlite quantity, %	30/70



a b

Fig. 3.1 Structure of base nodular iron modified by mischmetal FeCeMg-5. 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 mischmetal FeCeMg-5 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 1270...1300 °C and exposure during 27...30 seconds. The total time during which part of the sample was in liquid state is 35-40 seconds.

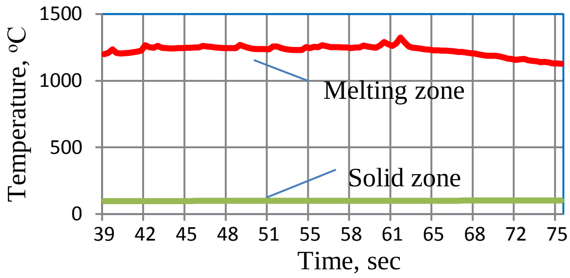


Fig 3.2 Graph of ductile iron high temperature heating and short term exposure mode

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.3.1).

Nodular graphite observed in all sample area that was re-melted. In general, the size of graphite inclusions decreased from 3...7 μm to 1,5...2 μm, graphite inclusions nodularity degree decreased from 90...95 to 65...85 % and the amount of graphite inclusions decreased from 80..120 to 5...15 pcs/mm^2 (fig. 3.3). In the melting area there are some graphite inclusions that have partially broken shape. The size of some graphite inclusions is increased considerably to range 25...50 μm (fig. 3.4). This nodular graphite size is bigger than in base ductile iron. The amount of such inclusions is in range from 5 to 10 pcs/mm^2 (fig. 3.4).

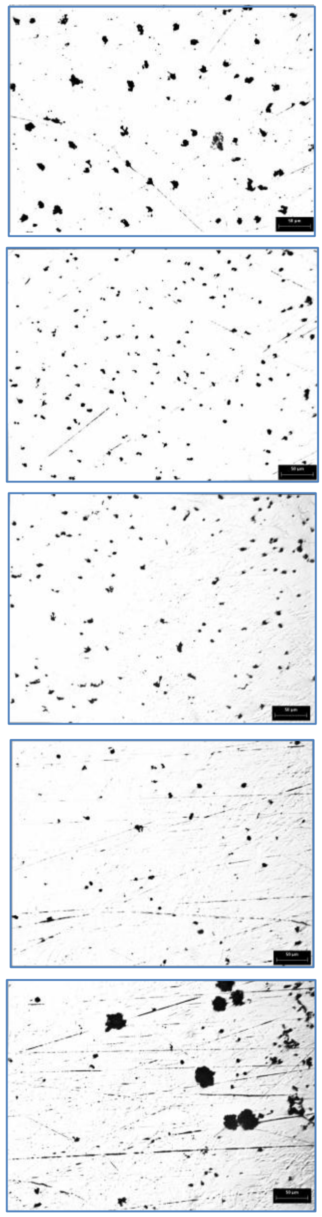


Fig 3.3 Graphite inclusions on the sample length after melting at the temperature 1270...1300 °C and exposure time 35...40 seconds: a - 0 mm (base ductile iron); b - 3 mm; c - 6 mm; d -9 mm; e - 12 mm.

Metal matrix structure along the length of the sample changes from ferrite-pearlite, in solid part to cement and ledeburite in apart, which was re-melted (fig. 3.5).

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TABLE 3.2 – GRAPHITE INCLUSIONS CHARACTERISTICS IN THE RE-MELTED SAMPLE AREA OF DUCTILE IRON MODIFIED BY MISCHMETAL FECEMG-5.

Distance, mm	Diameter, µm	GND, %	Average graphite amount,%
initial	3…7	90…95	80...120
3	1,5…3	85…90	80...120
6	1,5…3	85…90	60..80
9	1,5…3	85…90	10…20
12	1,5…2(25…50)	65…80	10…15(5-10)

Metallographic analysis showed that the spherical graphite includes is present in ductile iron that was modified by mischmetal FeCeMg-5 after re-melting, which began to lose spherical graphite shape and includes of flake graphite.

The characterization of re-melted ductile iron modified by mischmetal FeCeMg-5 is shown in table 3.3.

TABLE 3.3 – THE CHARACTERIZATION OF RE-MELTED DUCTILE IRON MODIFIED BY MISCHMETAL FECEMG-5

Temperature mode	Re-melting
Ductile iron matrix structure	cement and ledeburite
Graphite inclusions shape	nodular, flake

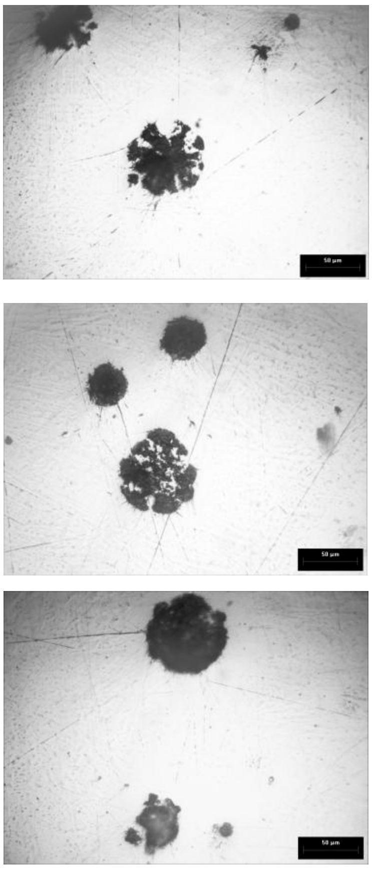

Fig. 3.4 Graphite inclusion (different field of view) in the sample molten area.

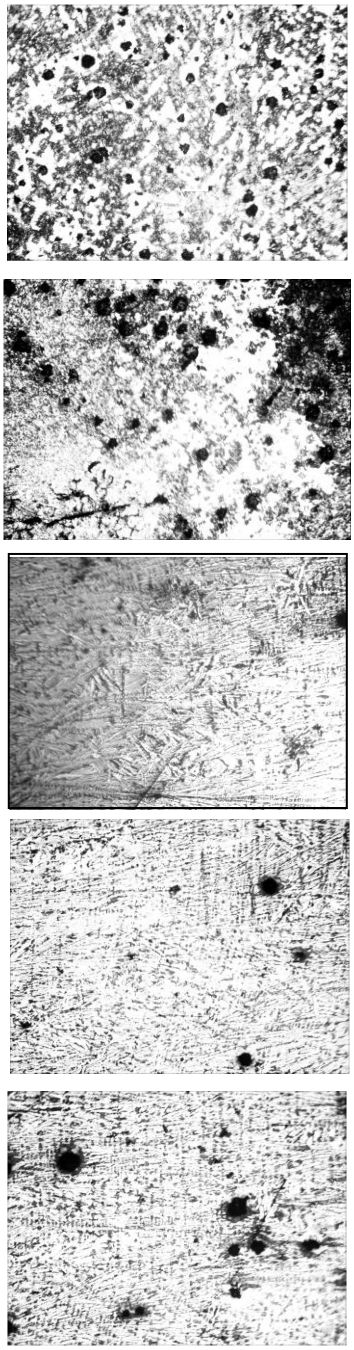

Fig. 3.5 The metal matrix structure (different field of view) on the length of re-melted sample area at the re-melted temperature 1270...1300 °C and exposure time 35...40 seconds.

3.2.2 Re-melting ductile iron modified mischmetal FeCeMg-5 at low temperature and long term conditions.

Sample modified by mischmetal FeCeMg-5, was heated to the temperature.1050...1100 °C (near magnesium boiling point) and exposure during 5 min 35 second (fig.3.13).

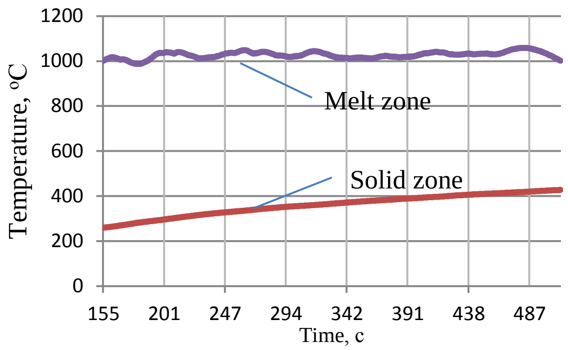

Fig. 3.6 Graph of ductile iron low temperature heating and long term exposure mode

Metallographic analysis showed that after nodular iron heating, re-melting and exposure at 1050...1100 °C, during 5 minutes 35 seconds, in the area of the sample that has been re-melted, there were no changes in the shape of graphite inclusions (fig. 3.14).

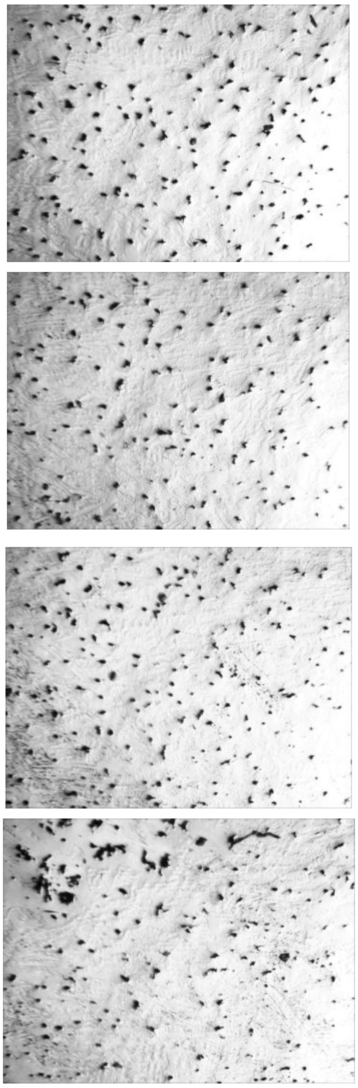

Fig. 3.7 Graphite inclusions in the ductile iron re-melted area (various view sight) at the temperature 1050...1100°C, by 1 mm

TABLE 3.3 – GRAPHITE INCLUSIONS CHARACTERISTICS IN THE RE-MELTED SAMPLE AREA OF DUCTILE IRON MODIFIED BY MISCHMETAL FECEMG-5 (EXPOSURE TEMPERATURE 1050...1100°C, TIME 5 MINUTES 35 SECONDS).

Distance, mm	Diameter, μm	GND, %	Average graphite amount,%
initial	3…7	90…95	80...120
1	3…7	90…95	80...120
2	3…7	90…95	80...120
3	3…7	90…95	80...120
4	3…7	90…95	80...120
8	3…7	90…95	80...120
9	3…7	90…95	80...120
11	3…7	90…95	80...120
12	3…7	90…95	80...120

Graphite nodularity degree is 90...95 %, the average graphite size is 3...7 µm, the graphite inclusion amount is 120...140 pcs/mm^2, that is no different from the baseline characteristics of ductile iron graphite, which is not melted.

4 CONCLUSIONS

- There are no complete destruction nodular graphite inclusions.in the liquid phase during ductile iron modified by mischmetal FeCeMg-5 re-melted at the temperature 1270...1300 °C during 35...40 seconds. There is a decrease their size from 7 µm to 2 µm, and decrease GND to 65...85 %. At the same time, there has been a sharp increase the diameter of individual nodular graphite inclusions to 25-50 mcm. This inclusions is situated near small one and evenly spaced in ductile iron.
- At ductile iron modified by mischmetal FeCeMg-5 re-melting at the temperature 1100°C (near magnesium boiling point) during 5 minutes 35 seconds, the of nodular graphite inclusions shape changing were not found. The size, amount and GND remain unchanged and fully conform to the characteristics of the basic ductile iron.

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