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ABOUT THE DUCTILE IRONS ELABORATED IN ELECTRIC ARC FURNACES – EXPERIMENTAL RESEARCH FOR INCREASING THE EFFICIENCY OF INOCULATION TREATMENTS

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ABSTRACT: *The following experiments were made in an electric arc furnace with basic wall lining, with a 5 tones capacity, which was set on a casting platform. The resulting irons are destined to the nodularizing modification of the graphite. Proper inoculation of graphitic cast irons cannot be over emphasized, because this step defines the final microstructure and resultant properties and minimizes problems. Inoculation, if done correctly, controls the nodule count, reduces or eliminates carbides, produces the correct mechanical properties, improves machinability, and will decrease shrinkage. The chosen modifier is a classical one, based on Fe, Si, and Mg. It will be presented the chemical compositions of irons that are subject to modification, the parameters of the modification process, and also the results (the final composition of ductile irons, the characteristics of the graphite and of the matrix, gases contents). The conclusions can be used for the making up of a modifying technology, on an industrial scale.*
KEYWORDS: *ductile iron, graphite form, magnesium, pre-alloy, electric arc furnace, efficiency*

INTRODUCTION & FOREWORD

Ductile iron is part of a group of materials which can be produced to have a wide range of properties through control of the microstructure. [1-2,7] The common defining characteristic of this group of materials is the morphological structure of the graphite, which is in the form of spherical nodules, rather than flakes (as in grey iron). In its liquid state, graphitic iron (lamellar, vermicular or nodular) is a liquid solution in which carbon atoms are dissolved in iron. Without any other alloy additions, an extremely slow cooling rate would result in the precipitation of carbon as graphite, following the Iron-Carbon (graphite) dual phase diagram. [1-2,7-9] However, the solidification of castings deviates from this rule. Under industrial conditions, the combination of the quality of the metallic charge, the melting and treatment of the liquid iron, and the addition of ferroalloys, results in a complex solidification route resulting in an "Iron-Cementite-Graphite" composite [1-3,7-14].

Besides the requirement that the graphite be manipulated into the spheroidal shape, the ferrite and pearlite ratios can be controlled through alloying, shakeout temperature control or post-casting heat treatment to vary the relative amounts pearlite and ferrite from 0% to 100%. The control of the pearlite and ferrite ratio manipulates the mechanical characteristics of the ductile iron to produce numerous standard grades of material. [1-4,7-9]

Inoculation can be accomplished in one or all of three ways: prior to the magnesium treatment (also called preconditioning), simultaneously with treatment, and after the treatment (called late inoculation). Normally the later in the process that inoculation is performed the more effective it will be. However, there are many procedures that must be followed to make the inoculation process effective. Proper inoculation of graphitic cast irons cannot be over emphasized, because this step defines the final microstructure and resultant properties and minimizes problems. Inoculation, if done correctly, controls the nodule count, reduces or eliminates carbides, produces the correct mechanical properties, improves machinability, and will decrease shrinkage. [3,5-9]

It is known that at the concocting of ductile irons, the electric arc furnaces are being used only at the making up of superior quality irons. When a low quality raw material is used, the electric arc furnace oven with basic wall lining is the only aggregate that allows the de-sulphuration and de-phosphoration processes. The following experiments were made in an electric arc furnace with basic wall lining, with a 5 tones capacity, which was set on a casting platform. The resulting irons are destined to the nodularizing modification of the graphite.

EXPERIMENTATIONS AND RESULTS

The materials from the oven were chosen so that they would satisfy low percentage of sulphur and other anti-modifier elements and in the same time high percentage of carbon in order to limit the carburizing process. The weighted 4700…5500 kg, and was made from 85…90% new and old cast iron and from 10…15% old iron. Depending on the ingredients of the raw materials, the chemical composition of the resulting cast irons was presented in Table 1.

Table 1. Chemical composition of the resulting cast irons

Chemical composition. %							S_C	η_{Mg} %
C	Si	Mn	P	S_i	S_f	Mg_{rez}		
3.68	1.56	0.66	0.110	0.030	0.004	0.048	0.98	25
3.72	1.73	0.70	0.110	0.022	0.002	0.043	1.01	21
3.60	1.92	0.68	0.110	0.020	0.013	0.005	0.98	23
3.64	1.87	0.92	0.127	0.021	0.019	-	0.99	27
3.80	2.03	0.79	0.120	0.025	0.008	0.063	1.05	38
3.70	1.34	0.76	0.095	0.021	0.011	0.059	0.96	28
3.72	1.80	0.75	0.130	0.033	0.010	0.037	1.01	23
3.60	1.94	0.79	0.150	0.030	0.010	0.080	0.99	40
3.66	1.66	0.78	0.140	0.023	0.009	0.031	0.98	21
3.73	1.95	0.68	0.113	0.022	0.011	0.048	1.02	28

For the modification it was chosen the pot modifying technology together with the help of the modifying bell. The modifier quantity was calculated taking into account the Sulphur percentage from the resulting cast irons as well as the parameters of the modifying process. The relationship is the following:

$$Q_{mod} = \frac{0{,}76(S-0{,}10) + Mg_{rez} + t.10^{-3}}{\eta . \frac{Mg_{prealloy}}{100}} . \left(\frac{T}{1450}\right)^2 .G \qquad (1)$$

where: S – the sulphur percentage in iron exposed to the modification,[%]
Mg_{rez} – the proposed magnesium in iron, [%]
t – the time required to maintain iron in, after modification, [min]
η – the assimilation efficiency of the magnesium, [%]
$Mg_{prealloy}$ – the quantity of magnesium in pre-alloy, [%]
T – modification temperature, [C]
G – the quantity of modified iron, [kg]

The pre-alloy quantity needed for modification is related to a number of process parameters which become the most probable sources of variability of the magnesium concentration in the casting. By maintaining accurate records of these key process parameters, the foundryman can then identify the possible causes of the observed variability.

Nowadays, most foundries use the Fe-Si-Mg (with 5…12% Mg) and Fe-Si-Ca-Mg (with 10…15% Mg) types pre-alloys for the modification treatment. In our experiments, the chosen modifier is a classical one, based on Fe, Si, and Mg. The used pre-alloy had the chemical composition, which is presented in Table 2. The limits of molted irons chemical composition, before modification, were presented in Table 3. The residual elements category is the one with the largest number of elements. In our experiments, the residual elements in ductile iron are presented in Table 4. Several of the elements are intentionally added to improve nodule count or/and stabilize pearlite (see the ad notations from the same Table 4).

Table 2. The chemical composition of used pre-alloy

Mg, %	Si
10.0...15.0	40.0...45.0
Ca	Fe
max 1.0	remainder

Table 3. The limits of molted irons chemical composition

Limits of chemical composition, %					S_C
C	Si	Mn	P	S	
3.15	1.34	0.68	0.095	0.020	0.98
3.70	1.92	0.80	0.110	0.030	1.05

Table 4. Residual elements in cast irons

Chemical composition, ppm								
Cr	Ni	Mo	Co	Ti	V	Cu	Pb	As
11	414	163	113	443	81	164	183	108
88	310	17	113	198	26	178	45	44
58	484	29	123	221	29	219	8	71
9	251	76	76	139	37	125	63	52
125	461	96	188	215	79	77	194	113
96	284	22	104	147	24	163	44	40
100	293	8	105	152	25	168	36	42
98	288	-	55	157	25	166	31	41
12	440	189	112	299	90	201	210	119

Note: Element promoting chunk graphite are: Ni; Elements promoting flake graphite are: As, Cu, Pb; Pearlite promoting elements are: As, Cr, Cu, Mo, Ni, Ti, V; Carbide promoting elements are: Cr, Mo, Ti, V;

The sequence of the modification operations of cast iron was the following:

- *molted iron, elaborated in the 5 tone furnace was melted in the 8 tone modification treatment ladle, after which the transportation of this on the casting platform was executed;*
- *in the modification area the molted iron was cleaned of the formed slag and the temperature was measured;*

- *after closing the modification treatment ladle, the actual modification was undertaken. The reaction during modification was strong due to the high temperature of the iron. The modification time was 3-4 minutes;*
- *after cleaning the pot of the slag formed during the modification, the casting was executed. The stop time between modification and casting process was 6-8 minutes and the duration of modification was 1-2 minutes.*

The total duration to maintain the molted status did not go over 12 minutes (see Table 5). The microstructures are shown in Table 6. The cast pieces out of the modified irons were exposed to a heat treatment for detention (see Table 6), according to the following pattern:

- *heating from 150 to 650°C with a speed of 100°C/h, for 5 hours;*
- *maintain at 650°C for 4 hours;*
- *cool from 650°C to 300°C with a speed of 100°C/h;*
- *free cooling from 300°C to the environmental temperature.*

Table 5. The parameters of the modification process

No	Temperatures, C		Durations, min			
	Modifying	Casting	Modifying	Stay	Casting	Total
1	1370	1300	3	7	2	12
2	1300	1250	2	8	1	11
3	1260	1200	2	6	1	9
4	1270	1190	2	7	1	10
5	1300	1240	3	7	2	12
6	1340	1280	2	8	1	11
7	1330	1260	2	6	2	10
8	1350	1260	2	6	2	10
9	1360	1310	3	7	1	11
10	1350	1280	3	7	1	11

No	Pre-alloy		Q_{iron}, to
	Type	Quantity	
1	Fe-Si-Ca-Mg	100	5.0
2	Fe-Si-Ca-Mg	100	5.0
3	Fe-Si-Ca-Mg	75	4.8
4	Fe-Si-Ca-Mg	85	5.0
5	Fe-Si-Ca-Mg	80	5.0
6	Fe-Si-Ca-Mg	85	4.5
7	Fe-Si-Ca-Mg	75	5.2
8	Fe-Si-Ca-Mg	80	5.0
9	Fe-Si-Ca-Mg	80	4.9
10	Fe-Si-Ca-Mg	75	4.5

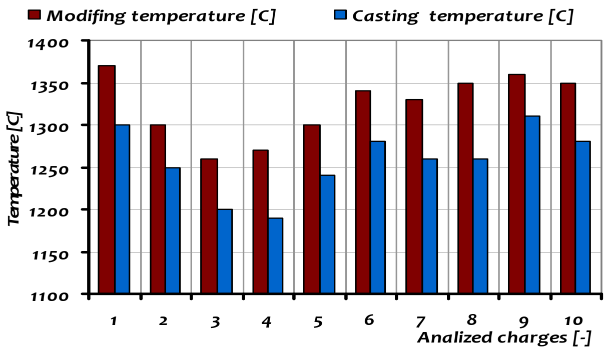

Fig. 1. The temperatures of the modification process

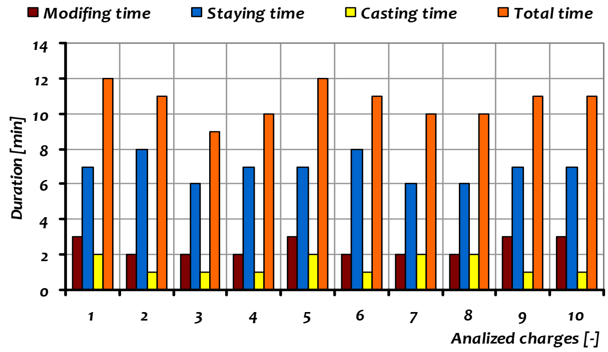

Fig. 2. The duration of the modification process

Table 6. Microstructures of the ductile irons and applied heat treating

No	Microstructure				Mg_{rez}, %	Heat treating
	Graphite forms	Surface occupied, %	Graphite diameter, μm	Matrix		
1	nodular + vermicular	10.91	75	ferrite	0.049	detension
2	nodular	9.52	60	ferrite	0.043	detension
3	flake	14.50	-	ferrite	0.005	detension
4	flake	11.91	-	ferrite	-	-
5	nodular	7.71	70	ferrite	0.063	detension
6	nodular	10.09	75	ferrite + pearlite	0.059	detension
7	nodular	13.02	90	ferrite + pearlite	0.037	detension
8	nodular + vermicular	11.44	62	ferrite + pearlite	0.080	detension
9	nodular + flake	6.52	70	ferrite + pearlite	0.031	detension
10	nodular, vermicular + flake	11.84	70	ferrite + pearlite	0.048	detension

CONCLUSIONS

After experimentations, we can draw the conclusions and make some suggestions for the ductile iron production in the electric arc furnaces, as follow:

- *the elaboration of ductile irons for modification in electric arc furnaces is possible especially due to the fact that the process for elaboration can be led much easier, resulting in less quantities of sulphur, the main restrictive element in the composition of chemical composition, as well as other hampering elements (P, O, H, N);*
- *overall chemistry control, modification treatment, and modifying agents adding are all important steps in the ductile iron processing, but all these can be dominated in importance to a certain extent through good inoculation;*

- *the efficiency of the inoculation treatment is very dependent by a good quality metallic charge and a well controlled melting process. To make the inoculation of ductile iron more efficient, it is recommended to optimize the charge composition, to rapidly melt the metallic charge and, when liquid, to hold it at as low a temperature as is practical.*
- *the effect of very small amounts of these harmful (tramp) elements can be significant. The concentrations of most of these elements are not often checked by the foundry. In many instances, analysis of these elements is impossible without specialized equipment, but based upon the nature of the problems that they can produce, the concentrations should be checked by an outside laboratory. The suggestion is to keep the amounts of all of these tramp elements as low as possible or at the least, tightly controlled.*
- *due to the less quantities of hampering elements within the composition, the quantities of pre-alloy unmodifying required to ensure the modification effect of the graphite are smaller;*
- *addition of the inoculants agents at the correct temperature for the casting section is one of the most important part of ductile iron production;*
- *keep the metal holding time after inoculation as short as possible, can be one of the principles of effective inoculation. The duration of the modification effect is longer and the graphite nodularizing is more secure;*
- *the temperatures at the moment of evacuation from the furnace can be more easily framed within the limits indicated by the specialized readings in modification process;*
- *sulphur control in the production of ductile iron has long been recognized as being essential. Higher sulphur levels call for increased additions of nodularizing alloy with consequent higher treatment costs and dangers of sulphite dross defects. In order to control and avoid the problems associated with sulphur in ductile iron therefore it is essential to regularly analyze the sulphur content of the liquid base iron prior to nodularizing;*
- *the proportion of nodular graphite is bigger than in the case of ductile irons obtained in other types of furnaces, and all the characteristics of the graphite (size, distribution) are better than the previously mentioned process;*

Therefore, the presence of trace elements, the addition of alloying elements, the modification of solidification behavior, and heat treatment after solidification are used to change the microstructure of cast irons to produce the desired mechanical properties in the common types of cast iron. Concluding, the proposed technology can be applied in all foundries for the elaboration of ductile irons in electric arc furnaces of any size.

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