Influencing factors on as-cast and heat treated 400-18 ductile iron grade characteristics

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Abstract: As-cast and heat-treated 400-18 ductile iron (DI) grade was obtained in different foundry conditions, as metallic charge, Mg-treatment alloy and inoculation. It was found that the Pearlitic Influence Factor (P_x) and Anti-nodulizing Complex Factor (K_1) have an important influence on property of DI, depending on the Mn and P level, the metallurgical quality of iron melt, rare earth (RE) and inoculation. It was also found that the influence of Mn is depended on the phosphorus and residual elements level in ductile iron. Less than 0.03%P and 0.2%Mn and P_x<2.0 are the basic conditions to obtain as-cast ferritic structure. At the same lower level of Mn and P, the increasing of residual elements (P_x>2.0) determines presence of pearlite in as-cast structure, while ferrite structure is obtained after a short annealing heat treatment. Lower level of phosphorus (P<0.025%) and residual elements (P_x<2.0) allow to use relative high Mn content (0.32%-0.38%), in condition of ferritic structure, including in as-cast state. High P (0.04%-0.045%) and Mn (0.25%-0.35%) content stabilized pearlite, especially at lower level of residual elements (P_x <2.0). Anti-nodulizing action of elements was counteracted up to K_1=2.0 level, by RE included in Mg-treatment alloy, which are beneficial for K_1<1.2 and compulsory for K_1>1.2. Si has a significant influence on the mechanical properties of heat treated ductile irons: an important decreasing of elongation level and a moderate increasing of yield and tensile strength and their ratio in 150-170 HB typical hardness field. A typical final chemical composition for as-cast 400-18 ductile iron could include 3.5%-3.7%C, 2.4%-2.5%Si, max.0.18%Mn, max.0.025%P, max.0.01%S, 0.04%-0.05%$Mg_{res.}$ for P_x<1.5 and K_1<1.1. High purity pig iron, RE-bearing FeSiMg and powerful inoculant are also recommended.

Keywords: ductile iron; 400-18 grade; metallic charge; pearlitic and anti-nodulizing factors; chemistry

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The ductile irons show complex chemical composition, so rigorous control is required for all the groups of elements acting differently in these materials [1]. The starting point should be the distribution of elements during solidification process, inside the eutectic cells (Si, Ni, Cu) or outside, within the intercellular regions (P, Mn, Ti, Cr, Mo, V) where these last elements help the carbides promotion, pearlite stabilization in ferritic irons or determine intercellular lamellar graphite formation. Regarding the obtaining of ferrite ductile irons, most important are the elements, which cause pearlite stabilization, with a cumulative effect according to a Pearlitic Influence Factor (P_x) [2]:

$$P_x = 3.0\,(\%Mn) - 2.65\,(\%Si-2.0) + 7.75\,(\%Cu) + 90\,(\%Sn) + 357\,(\%Pb) + 333\,(\%Bi) + 20.1\,(\%As) + 9.60\,(\%Cr) + 71.7\,(\%Sb) \quad (1)$$

As the promoting effectiveness of pearlite, phosphorous must be especially considered as 10 times more powerful than Mn, while Cr is in the same position as Ni (Table 1) [3, 4].

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Table 1 Relative pearlite promoting effectiveness of representative elements [3]

No.	Element	Relative pearlite promoting effectiveness
1	Sn	39.00
2	Mo	7.90
3	P	5.60
4	Cu	4.90
5	Ti	4.40
6	Mn	0.44
7	Ni	0.37
8	Cr	0.37

The anti-nodulizing influence of elements must be also considered, for ensuring graphite nodularity as defined for ductile iron, respectively more than 80%NG and less than 20%VG, without lamellar graphite. The matter turns critical when higher values are requested for graphite nodularity (up to 100% NG), and most of all when maximum compactness for nodular graphite must be reached (of the type K-ASTM). Generally, the Complex Factor K_1 (Thielman) shouldn't exceed the value of 1.0, in Mg-treated irons [2, 5]:

$$K_1 = 4.4\,(\%Ti) + 2.0\,(\%As) + 2.4\,(\%Sn) + 5.0\,(\%Sb) + 290\,(\%Pb) + 370\,(\%Bi) + 1.6\,(\%Al) \quad (2)$$

A distinct position in the category of anti-nodulizing elements is taken by the ones favoring the occurrence of intercellular lamellar graphite (Bi, Pb, Sb, As, Cd, Al, Sn, Cu). As regards ductile iron alloying, major actions are caused by both ferrite alloying elements (Si, Ni) and pearlite alloying elements (Ni, Cu, Sn, Mo, V). Silicon alloying ferrite determines the increase of tensile strength and hardness, but drastically decreases the elongation (embrittling effect), while nickel contributes to the increase of tensile strength level and yield strength limit, with no obvious negative influence on elongation. Consequently, Ni frequently present in ferritic ductile irons, when obtaining tensile strength at high elongation proves a serious problem.

The main objective of present work is to identify the influencing factors on as-cast 400-18 ductile iron production, such as the composition of metallic charge, Mg-treatment alloy and inoculants and final chemical composition of ductile iron, in foundry conditions.

1 Experiments

Acid lining, coreless induction furnaces (low and medium frequency) were used to produce the base iron melt in several foundries. Different metallic charges were tested, including:

(1) 0-30% molten iron “heel”, as grey iron or ductile iron specific characteristics;

(2) 26%-40% ferritic ductile iron returns;

(3) 18%-40% steel scrap at different qualities;

(4) 0-47% high purity pig iron (Sorelmetal type).

Sandwich and Tundish Cover techniques were used for Mg-treatment of iron melt (1.7%-2.2% FeSiCaMg or FeSiCaMgRE as nodulizers). The 0.5%-0.8% FeSi75 or Ca, Ba-FeSi alloys were used for Ladle Inoculation. Complex chemical analysis was recorded, to determine not only the content of the base elements in ductile iron (C, Si, Mn, P, S, Mg) but also the most important residual elements from all of influence groups (pearlite promoting and anti-nodulizing, especially). Table 2 shows the specification of the experiments, as metallic materials included in the charge of furnaces.

Table 2 The quality of metallic charge

Experiment	Features of metallic charge
1	• Lower (0.13%-0.20%) and higher (0.20%-0.35%) content of Mn. • Lower content of P (0.025%-0.03%). • Higher level of residual elements. • Without high purity pig iron in the charge.
2	• Higher content of Mn (0.25%-0.30%). • Higher content of P (0.04%-0.045%). • Lower level of residual elements. • High purity pig iron in the charge.
3	• Lower level of Mn (0.15%-0.18%). • Lower level of P (0.017%-0.018%). • Medium level of residual elements. • High purity pig iron in the charge.
4	• Higher level of Mn (0.32%-0.38%) • Lower level of P (0.020%-0.022%) • Lower level of residual elements. • High purity pig iron in the charge.

P_x and K_1 complex factors were applied to evaluate the pearlite promoting effectiveness and anti-nodulizing influence, respectively. Steel scrap mainly determines the level of Mn, P and residual elements, which were found to have the highest influence on the mechanical properties of ductile irons not only in the as-cast state but also after heat treatment.

There were different types of steel scrap, such as thin steel sheet at lower content of P, S and residual elements but at two levels of Mn (0.15%-0.25% and 0.4%-0.45%), and commercial steel scrap (0.6%-0.9%Mn, up to 0.3%Cr, Cu, Ni). Steel scrap has two kinds: contaminated and non-contaminated with non-ferrous elements, especially Pb and Sn. High purity pig iron (Sorelmetal type) was considered for two reasons: to dilute the chemical composition of base iron and to improve the ̀metallurgical quality [8-10].

Two variants of Si-base Mg-treatment alloys were tested, with 0.5%-1.5%RE and without rare earth content in order to introduce an efficient tool to control the action of anti-nodulizing residual elements. On the other hand, different inoculation treatments were applied with different inoculant (FeSi75 or CaBa-FeSi) and addition rate (0.5%-0.8%), for different conditions to obtain the base iron melt, such as with different steel scrap/high purity pig iron ratio and residual elements level.

2 Results

Table 3 shows the representative results between chemical composition features and obtained mechanical properties, in as-cast state and after annealing (ferritizing) heat treatment, under the influence of metallic materials shown in Table 2.

The first experiment included foundry heats, which are characterized by a lower level of phosphorus (<0.03%) and a large range of carbon (3.2%-4.5%) and silicon (1.95%-2.75%), so equivalent carbon reached 3.9%-5.1% range. Under the influence of manganese (0.13%-0.35%) and residual elements, such as Pb (0.001%-0.007%), Sn (0.001%-0.01%), Cu (0.04%-0.24%), Cr (0.015%-0.053%), Al (0.013%-0.035%) and As (0.007%-0.012%), three levels of sensitiveness were obtained to pearlite promoting (P_x) and as anti-nodulizing action (K_1) of final chemical composition (Table 3). Lead was found in any sources of scrap such as terne plate and old painted structural steel, which are contaminated steel scrap. Regarding the effect of Pb on the matrix structure, it is known that this element causes a decrease of ferrite content, which also depending on the cooling rate [6, 7].

Ferrite amount in as-cast state is mainly determined by the equivalent carbon (CE) and residual elements included in pearlitic influence factor P_x (Fig. 1). More than 90% ferrite is obtained only for P_x<2.0, at a large of carbon and silicon content (CE=3.9%-4.5%). The increasing of equivalent carbon level leads to more ferrite amount in as-cast structure for P_x= 2.0-3.0 (40% to 80% ferrite) while without influence for P_x>3.0. Regarding the elements influence on the pearlite formation, Pb was found to have the highest power, followed by Sn, Cu and Mn, while anti-nodulizing complex factor K_1 is also mainly determined by Pb level.

Table 3 Characteristics of 400-18 grade ductile irons

Experi-ment	P %	Mn %	Pearlitic Influence Factor P_x	Anti-nodulizing Factor K_1	Mechanical Properties				Iron status
					Tensile strength R_m, MPa *[min.400]	Yield strength $R_{p0.2}$, MPa *[min.250]	$R_{p0.2}/R_m$ ratio [min.0.625]	Elongation *A*, % *[min.18]	
I	0.025-0.03	0.015-0.20	0.1-1.9	0.3-1.1	420-560	285-312	0.68-0.72	18-24	As-cast
		0.13-0.20	2.0-3.0	1.2-1.9	420-481	276-342	0.57-0.72	20-29	Heat treated
		0.20-0.35	>3.0	1.5-2.4	453-534	285-351	0.57-0.75	17-21	Heat treated
II	0.04-0.045	0.25-0.30	1.5-2.0	0.95-1.05	560-570	350-355	0.63-0.70	12-14	As-cast
					462-460	276-285	0.59-0.64	19-21	Heat treated
III	0.017-0.018	0.15-0.18	2.0-2.2	1.5-1.8	473-490	331-351	0.69-0.73	16-18	As-cast
					418-430	284-295	0.65-0.72	22-24	Heat treated
IV	0.020-0.022	0.32-0.38	1.5-1.9	0.7-0.9	453-490	298-352	0.66-0.72	21-23	As-cast

*[ ]–ISO 1083 conditions

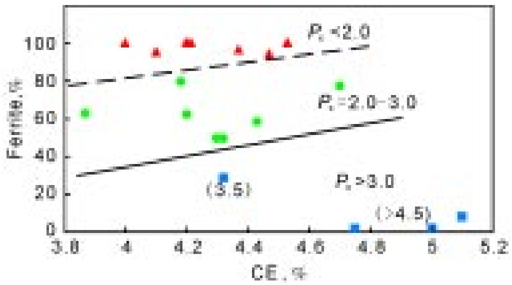

Fig. 1 Influence of carbon equivalent (CE) and pearlitic influence factor (P_x) on the ferrite amount in as-cast state

For less than 0.03%P content and max. 0.2%Mn, the lower level of residual elements (P_x<2.0, K_1<1.1) determines prevalent ferrite structure in as-cast state and mechanical properties according to 400-18 ductile iron. At the same lower content of P (<0.03%) and Mn (<0.2%), higher level of residual elements leads to P_x>2.0 and K_1>1.2, so only by annealing heat treatment, can the ferrite structure and the specific mechanical properties for this ductile iron grade be obtained. More than 0.2%Mn and corresponding P_x>3.0 means a pearlitic as-cast structure, but it was also possible to obtain a full ferrite matrix by heat treatment, with ductility at lower limit of acceptance.

A typical problem for ductile irons ferrite structure resulted from heat treatment is difficulty to make the strength properties accord with ductility level, which contradictory influenced by chemical composition, such as silicon (Fig. 2). As a representative alloying element for ferrite, the increasing of silicon content (2.2% up to 2.75%) has a beneficial influence especially on the yield strength, tensile strength and their ratio, but has a detrimental action on the ductility, without a visible hardness effect. A relative higher silicon level (2.4%-2.5%Si) appears to be favorable to ensure necessary strength properties, for more than 18% elongation of easy access level. The use of rare earth in the Mg-treatment alloy was beneficial for lower level of residual element (K_1=0.5-1.2) and compulsory for K_1>1.2, especially due to Pb existed in these ductile irons. It was found that Pb-contaminated steel scrap is extremely dangerous in higher ductility irons. The absence of high purity pig iron in the first experiment hampered the ìmetallurgical qualityî of the base iron melt which was only partially compensated by the increasing of inoculation (no FeSi75 application, more than 0.5% Ca, Ba-FeSi addition was necessary).

The second experimental program was realized in a foundry which used 9%-10% cupola molten iron (0.66%Mn, 0.09%P, 0.18%S, 0.2%Cu) to create the heel in a 50 Hz coreless induction furnace to start ductile iron production. As for solid metallic materials addition, 28% ductile irons (0.33%Mn, 0.037%P), 18% steel scarp (0.28%Mn) and 44% high purity pig iron were used. It was obtained a base iron melt at relative high phosphorus (0.04%-0.045%P) and manganese (0.25%-0.30%Mn) content for lower level of residual elements, which allowed to reach limited values for complex control factors (P_x=1.5-2.0, K_1= 0.95-1.05). The improving of the metallurgical quality of the iron melt due to the beneficial influence of pig iron presents in the charge allowed to obtain good mechanical properties after heat treatment in the most of cases, especially at high P and Mn conditions [8, 9]. Phosphorus was found as the main reason for lower elongation of ductile irons in as-cast state, obtained from this program.

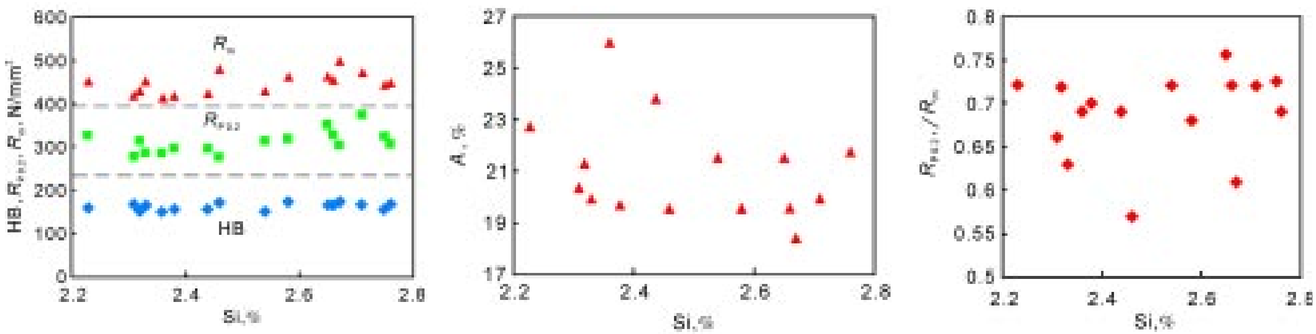

Fig. 2 Influence of Si on mechanical properties of the heat treated ductile irons

Lower content of phosphorus (<0.02%P) and manganese (<0.2%Mn) were obtained in the third program, but at a medium level of residual elements, which determined the increasing of pearlitic influence factor (P_x >2.0) and anti-nodulizing action factor (K_1>1.5). Metallic charge included 29% ductile iron returns, 24% low quality steel scrap and 47% high purity pig iron. Balanced ferrite and pearlite ratio was obtained in as-cast structure, at lower stability grade of pearlite. Short ferritizing heat treatment is usually applied in this case, to obtain more than 90% ferrite and adequate mechanical properties for these ductile iron grades.

Foundry experiments pointed out that at lower level of phosphorus (<0.025%P) and residual elements, as pearlite promoting effectiveness (P_x<2.0) and anti-nodulizing action (K_1 < 1.0), relative high manganese content could be accepted (0.32%-0.38%Mn) including in as-cast state (Experiment IV, Tables 2 and 3). Metallic charge included 40% ductile iron returns, 40%-50% steel scrap (0.4%-0.5%Mn, lower P and residual elements level) and 10%-20% Sorelmetal. Good 'metallurgical quality' of iron melt under the influence of this special pig iron (including new addition and also included in the returns), RE-FeSiMg treatment and Ca, Ba-FeSi inoculation allowed to obtain prevalent ferrite matrix, more than 95% nodularity and more than 200 nodules/mm^2, which covered the detrimental action of high manganese level, including in as-cast state.

3 Conclusions

(1) As-cast and heat-treated 400-18 grade ductile iron could be obtained in different foundry conditions as metallic charge, Mg-treatment alloy and inoculants, which must be accorded among them.

(2) Different rate and quality of metallic materials in coreless induction furnace charge led to different combinations of Mn, P and residual elements content, from low levels (Mn<0.2%, P<0.03%, P_x<2.0) up to medium and high levels (0.4%Mn, 0.045%P and P_x > 3.0).

(3) It was found that the influence of manganese is depended on the phosphorus and residual elements level:

Less than 0.03%P, no more than 0.2%Mn and P_x<2.0 are the basic conditions to obtain as-cast ferrite structure, according to 400-18 ductile iron.

At the same lower level of Mn and P, the increasing of residual elements (P_x>2.0) determines presence of pearlite in as-cast structure, while ferrite structure is obtained after a short annealing heat treatment.

Lower level of phosphorus (P<0.025%) and residual elements (P_x<2.0) allow to use relative high manganese content (0.32%-0.38%), for ferrite structure conditions, including in as-cast state.

High phosphorus (0.04%-0.045%) and manganese (0.25%-0.35%) content stabilized pearlite, inclusively at lower level of residual elements (P_x<2.0).

(4) Anti-nodulizing action of residual elements was counteracted by rare earth up to K_1=2.0 level for anti-nodulizing complex factor: they are beneficial for K_1<1.2 and compulsory for K_1>1.2.

(5) The presence of high purity pig iron in the charge is extremely beneficial, not only to control the complex factors P_x and K_1 but also to improve the 'metallurgical quality' of iron melt. It was found that the use of this material allow to accept higher P_x level or lower powerful inoculation operation.

(6) Silicon has a significant influence on the mechanical properties of heat treated ductile irons: an important decreasing of elongation level and a moderate increasing of yield strength for 150–170 HB typical hardness.

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