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Producing As-Cast Ferritic Nodular Iron for Safety Applications

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Abstract

Although Si has a strong ferrite promoting effect that results on increases of impact energy it provokes ferrite embrittlement at low temperatures[1,2]. Also increases of nodule numbers have a double effect, as it has a ferrite promoting effect due to the reduction of the distance for C diffusion and it results in reduction of the energy to fracture on the ductile region as the number of potential crack nucleation sites is increased (nodule/matrix interface) [2].

Considering these aspects the present study attempts to characterize the role of different levels of Si, in stream inoculation with FeSi and trace levels of Cu and Mn on impact properties of as-cast Ferritic Nodular Iron designed for safety applications where a minimum energy of 12J must be reached on Charpy impact test at –40°C using U-notched 10x10x55 mm test pieces.

The design of the experiments and the results analysis were done using Taguchi techniques. Two series of experiments were carried out and the effects on microstructure and static and dynamic mechanical properties were analyzed.

The results presented reveal the strong influence of Si and in stream inoculation on materials properties. The Si content that optimized its effect was nearby 2.4%. In stream inoculation resulted in increase of the energy at low temperatures. The best results in the work frame with energies above 12J at –40°C were obtained with a Si content of 2.4%, in stream inoculation ($\geq$ 0.1% FeSi) and low traces of pearlite promoting elements ($\leq$ 0.13% Mn and $\leq$ 0.04% Cu).

Introduction

The production of Ferritic Nodular Iron started using heat treatments to provide the ferritic matrix. In this conditions low variations of pearlite promoting elements as Cu, Mn and Sn was not critical, considering some restrictions. On the other hand, Si content have been traditionally specified at low levels (2.0-2.2%), minimizing its embrittlement effect to allow lower ductile-brittle transition temperatures. At the same time, strong inoculations have been avoided as it increases the nodule number reducing the energy on the ductile region as the nodules have a role as potential crack nucleation sites at high temperatures.

However, on the modern foundry the heat treatment is being avoided due to its high cost, demanding that even ferritic nodular iron components for safety applications should be used in the as cast condition. Taking this into account it was considered necessary the revision of the concepts for the alloy design, aiming low pearlite contents and high energies at low temperatures on as-cast condition. The main variables reviewed were Si content and nodules number.

Considering these facts this study attempted to determine an optimum point where the resulting effect of those variables is favorable for the increase of the energy at low temperatures. The analysis also considered the effect of trace levels of pearlite promoting elements as Cu and Mn. Although Sn has a strong pearlite promoting effect it was not considered on this study.

Experimental Procedures

Two series of experiments were carried out to investigate the effect of the selected factors. Table I shows the experiments designed in an orthogonal L8 matrix. The levels of the factors were selected to represent industrial conditions.

The materials were obtained from the melting of a metallic charge of 55% pig iron and 45% steel scrap in a 2.5 t medium frequency induction furnace. Additions of alloys were made to obtain the desired chemistry. The covered-ladle nodularization treatment was conducted in a 200 kg treatment ladle. At this moment additions of Cu and Mn were done on selected materials, the different levels of Si were obtained adding Si alloy directly on the furnace. The inoculation treatment using FeSi (1-6 mm) was made during the metal transference to the pouring ladle followed by the metal pouring on no-baked sand Y-blocks molds was at 1400^oC. At this moment the in stream inoculation with FeSi (0.2-0.7 mm) was made on selected materials. To avoid differences on Si content the total inoculant addition was kept constant (ladle + in stream = 0.5%). Charpy tests were carried out on temperatures between 60^oC and –80^oC with 10x10x55 mm U-notched specimens machined by broaching, according DIN 50115/April 1991.

Results and Discussions

Table II shows the chemistry and table III shows the microstructural and mechanical results for both series. The results were analysed using statistical tools as level means that shows the effect of each variable measured by the difference of the results means between the 2 levels, and contribution percentage that presents the influence of each variable over the results.

Figure 1 shows the level mean and contribution percentage results for pearlite content analysis for both series. These results show the strong effect that Si and in stream inoculation had on reducing the pearlite amount. In both series the additions of Cu and Mn had a small effect on the increase of pearlite amount.

Figure 2 shows the results related to the nodule number analysis. It can be seen that the in stream inoculation treatment had the strongest effect on the increase of nodule number. The effect of Si addition was also considerable. Additions of Cu and Mn on both series had no effect on nodules number variation.

After impact tests the fractures were analyzed on SEM and the fracture orthogonal plane surfaces were analysed on optical microscope. These analyses show that ductile fractures occurred associated to intense plastic deformation, followed by nodules decohesion and narrowing of the internodular metallic matrix leading to its shearing rupture. At room temperature, or above, the nodules had a role as nucleus to voids nucleation, leading to ductile fractures at lower energies. These fractures propagated through high nodule density paths. The reduction of test temperature restricted the deformation of the metallic matrix, conducting to cleavage fracture. The ductile-brittle transition occurred in a temperature range influenced mainly by the pearlite amount, nodules number and Si content. With the progressive reduction of test temperature the shearing resistance of the material became higher than its cohesive resistance to tensile microrupture, resulting in completely brittle fractures.

Brittle fractures were not associated to nodules as its fracture surface shows a small number of them. In fact, at low temperatures nodules have a role as cracks arresters, having an important effect on increasing the energy at low temperatures and on reduction of the ductile-brittle transition temperature[3].

On figure 3 it can be noted that higher energies at room temperature on series A are related to materials with lower pearlite amount, obtained with the highest level of Si. Material 4A had the lowest perlite amount and higher nodules number, presenting the highest energies and lowest transition temperature. This material presented mainly ductile fracture at -40^{o}C, as shown on figure 4. The results obtained by this material, on the as cast condition and produced in an industrial environment, are according to material standards for safety applications that require a minimum energy of 12J at –40°C. All the other mechanical properties tested are also according to these standards.

On series B the highest energies at any temperature were obtained by the material 4B with the lowest perlite amount and highest nodule number on series B. It was noted that the materials with highest energies at room temperature were the ones with highest Si content. These results are according Pan[1] that mention at room temperature high energies can be obtained with up to 3%Si. However, despite the material 4B, it was noted that materials with 2.7%Si had a transition from ductile to brittle at temperatures as high as 20 to 0°C although its low pearlite content. Having a transition temperature above –40° C, as shown on figure 5, the material 4B had not reached energies above 12J, what suggests that 2.7% Si on series B is over the optimum point, resulting in an embrittlement effect if compared with the results of series A.

Figures 6 and 7 present the statistical results related to Charpy tests carried out on series A and B respectively. It can be seen that the increase on the Si content from 2.2 to 2.4% on series A and from 2.1 to 2.7% on series B resulted in a strong effect of increasing the energy at room temperature, presenting a good correlation with the effect of Si on the reduction of perlite amount.

However, at lower temperatures the increase on Si content had a lower effect over the energy results. It suggests that its embrittlement effect is increasing with the reduction of the test temperature, reducing the final contribution of Si. It can be seen that at –40°C the addition of Si on series A had a favorable contribution for the increase of energy, while on series B it had not presented significant effect.

The in stream inoculation treatment had lower effect on the increase of the energy at room temperature than the additions of Si. It can also be noted that at room temperature the effect of in stream inoculation on increasing the energy was lower than its effect on reducing the perlite amount. These results confirm the mechanism suggested by the literature that graphite nodules act as nuclei to voids leading to dimples formation at room temperature[3] that is the predominant fracture mechanism at this temperature. However, with the reduction of the test temperature the fracture mechanism assumes a characteristic more brittle and the nodules act as crack arresters, promoting ductile fractures at lower temperatures, reducing its transition temperature [3]. This nucleation promoting to arresting promoting behavior change induced by graphite nodules increased the effect of in stream inoculation on the results of energy at lower temperatures.

Conclusion

- The increase on Si content (2.2 to 2.4% and 2.1 to 2.7%) resulted on increase of the Charpy energy. At temperatures above 0^oC its ferrite promoting effect was stronger than its embrittlement effect. At lower temperatures its effect of increasing the nodules number and promoting ferrite resulted in significant increase on the crack arrest effect, superposing its embrittlement effect. The optimum point noted was with a content of 2.4%Si;
- The in stream inoculation treatment had a strong effect on the increase of nodules number and reduction of pearlite content. It increased the energies at low temperatures when the nodules acted as cleavage cracks arresters;
- The selected levels of Cu and Mn had significant influence on the reduction of the energy on test temperatures bellow 0^oC;

- At the test temperature –40°C stated in safety application standards it was noted that: variation from 2.2 to 2.4%Si increased the impact energy; variation from 2.1 to 2.7%Si had a nil resulting effect over the impact energies; in stream inoculation treatment increased the impact energy; increase on contents of Mn and Cu reduced the impact energy;
- Material 4A obtained with in stream inoculation treatment, 2.4%Si, 0.04%Cu and 0.13%Mn reached properties according standards for safety application materials (>12J at –40°C), without heat treatment.

Acknowledgement

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Table I – Design of experiments – L8 orthogonal matrix

Series A					Series B				
Mat	**%Si**	**%Mn**	**%Cu**	**Inoc (%) Ladle+in stream**	**Mat**	**%Si**	**%Mn**	**%Cu**	**Inoc (%) Ladle+in stream**
1A	2.2	0.13	0.04	0.5 + 0.0	**1B**	2.1	0.15	0.05	0.5 + 0.0
2A	2.2	0.20	0.04	0.4 + 0.1	**2B**	2.1	0.30	0.05	0.4 + 0.1
3A	2.4	0.20	0.04	0.5 + 0.0	**3B**	2.7	0.30	0.05	0.5 + 0.0
4A	2.4	0.13	0.04	0.4 + 0.1	**4B**	2.7	0.15	0.05	0.4 + 0.1
5A	2.2	0.20	0.08	0.5 + 0.0	**5B**	2.1	0.30	0.12	0.5 + 0.0
6A	2.2	0.13	0.08	0.4 + 0.1	**6B**	2.1	0.15	0.12	0.4 + 0.1
7A	2.4	0.13	0.08	0.5 + 0.0	**7B**	2.7	0.15	0.12	0.5 + 0.0
8A	2.4	0.20	0.08	0.4 + 0.1	**8B**	2.7	0.30	0.12	0.4 + 0.1

Table II – Chemistry

Series A					Series B				
Mat	**%C**	**%Si**	**%Mn**	**%Cu**	**Mat**	**%C**	**%Si**	**%Mn**	**%Cu**
1A	3.5	2.15	0.13	0.04	**1B**	3.3	2.1	0.15	0.05
2A	3.5	2.2	0.20	0.04	**2B**	3.4	2.1	0.29	0.05
3A	3.5	2.4	0.20	0.04	**3B**	3.4	2.7	0.30	0.05
4A	3.5	2.4	0.13	0.04	**4B**	3.4	2.7	0.15	0.05
5A	3.4	2.3	0.20	0.08	**5B**	3.4	2.1	0.30	0.12
6A	3.4	2.2	0.13	0.08	**6B**	3.4	2.1	0.15	0.12
7A	3.3	2.4	0.15	0.08	**7B**	3.4	2.7	0.15	0.12
8A	3.4	2.4	0.20	0.08	**8B**	3.3	2.7	0.30	0.12

Trace elements are the same for all materials:				Trace elements are the same for all materials:			
%Sn	**%P**	**%Pb**	**%Cr**	**%Sn**	**%P**	**%Pb**	**%Cr**
0.006	0.04	0.0005	0.009	0.007	0.04	0.0006	0.015
%Mg	**%S**	**%As**	**%Sb**	**%Mg**	**%S**	**%As**	**%Sb**
0.037 to 0.042	0.010	<0.0018	<0.001	0.040 to 0.045	0.010	<0.0025	<0.001

Table III – Microstructural and mechanical results

Mat	**Pearlite %**	**Nodules /mm^2**	**Noduliz %**	**Nodules Size ASTM**	**Hardness HB$_{10/3000}$**	**UTS MPa**	**YS MPa**	**Elong %**	**Hv ferrite (Hv$_{0,2}$)**
1A	36	77	>90	6	191	522	332	15	149.6
2A	23	121	>90	6 -7	166	488	324	18	157.6
3A	13	118	>90	6 - 7	161	473	325	20	157.2
4A	8	138	>90	6 - 7	158	428	301	24	157.2
5A	32	75	>90	6	186	530	344	16	163.6
6A	19	136	>90	6 - 7	158	470	309	17	155.8
7A	28	121	>90	5 - 6	172	518	337	16	159.4
8A	11	150	>90	6 - 7	175	477	325	20	161.6
1B	40	89	>90	5 - 6	180	540	333	14.3	195.3
2B	50	102	>90	5 - 6	182	565	343	14.1	190.7
3B	29	100	>90	5 - 6	183	532	364	14.5	211.3
4B	9	121	>90	6	160	470	337	17.7	197.5
5B	57	84	>90	5 - 6	199	619	360	12.2	182.3
6B	43	103	>90	5 - 6	177	558	333	13.1	185.0
7B	25	99	>90	5 - 6	174	528	357	15.9	215.5
8B	20	106	>90	6	177	532	356	17.1	221.3

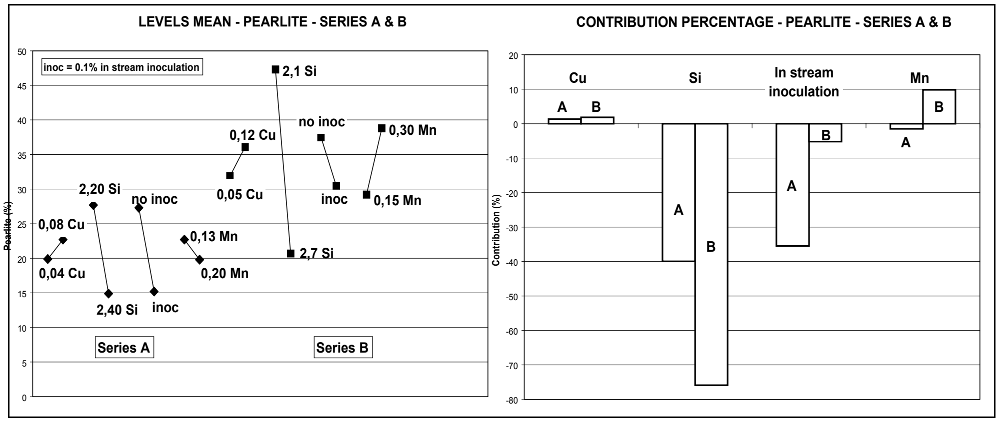


Figure 1 – Levels mean and contribution percentage analysis for pearlite amount

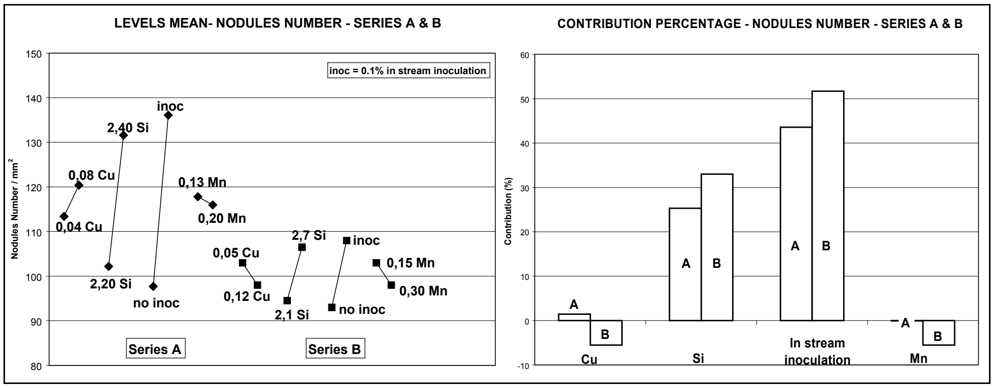


Figure 2 – Levels mean and contribution percentage analysis for nodules number

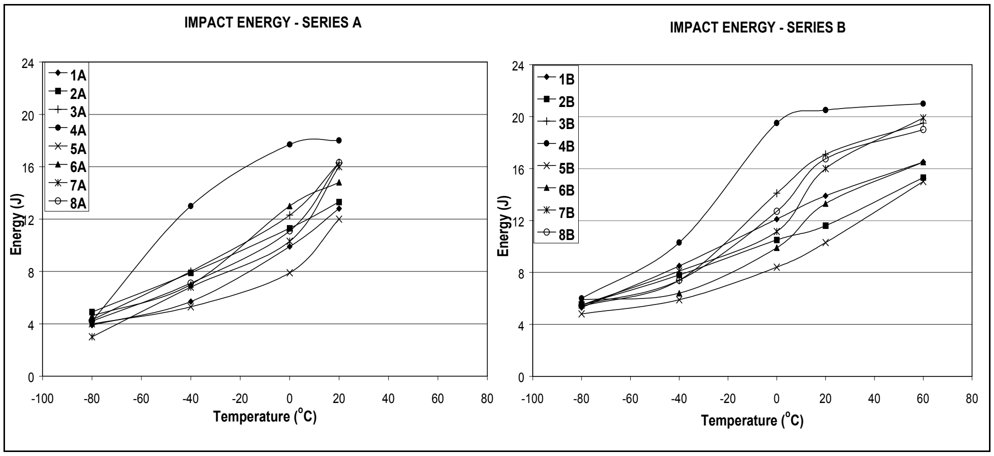


Figure 3 – Results of Charpy impact energy

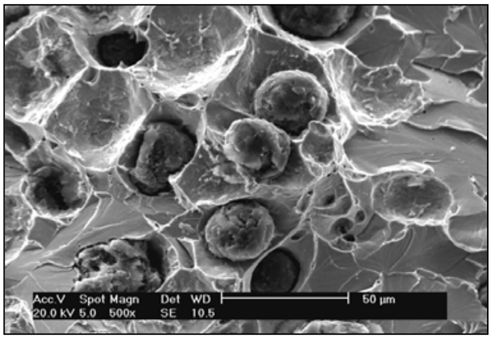


Figure 4 – Mixed fracture with dimples and cleavage.
Material 4A – Charpy test at – 40^{o}C

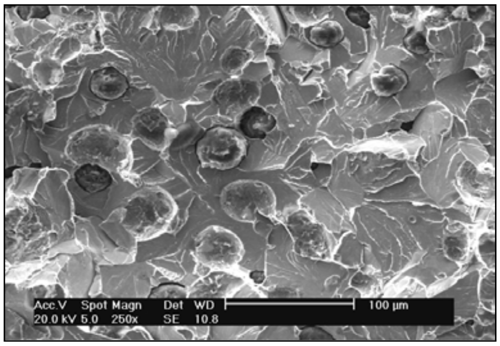
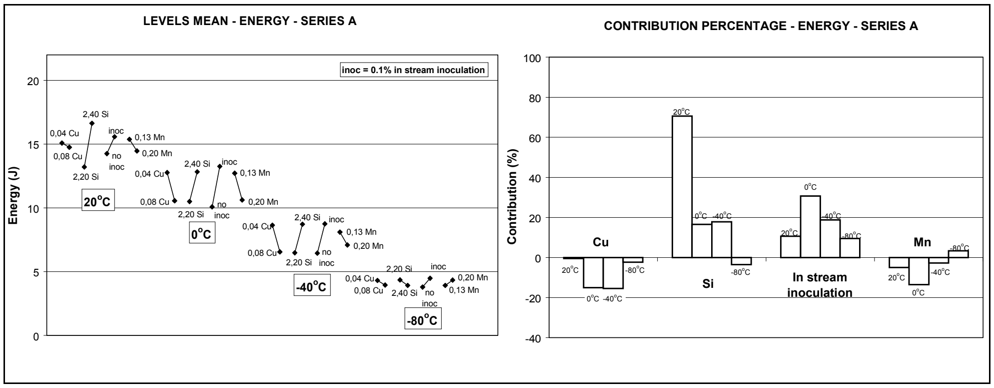
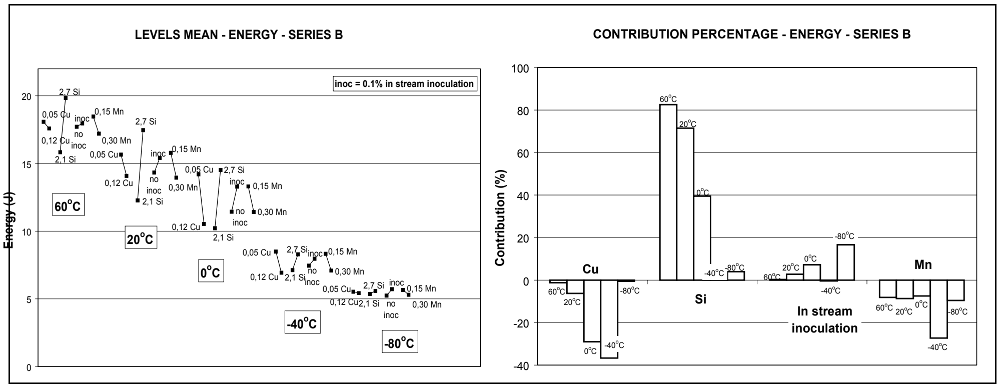


Figure 5 – Cleavage fracture.
Material 4B – Charpy test at – 40^{o}C



Levels means Contribution percentage

Figure 6 – Levels mean and contribution percentage analysis for Charpy impact energy on series A



Levels mean Contribution percentage

Figure 7 – Levels mean and contribution percentage analysis for Charpy impact energy on series B