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# As cast high silicon ductile irons with optimised mechanical properties and remarkable fatigue properties

U. de la Torre<sup>1</sup>, A. Loizaga<sup>1</sup>, J. Lacaze<sup>2</sup> and J. Sertucha\*<sup>1</sup>

The present work shows a comparative study regarding the mechanical properties of 25 as cast ferritic ductile iron alloys, nine of them with silicon contents higher than 3.00% and carbon contents lower than 3.60%. In a first step, different carbon equivalent values have been used in order to analyse the effect of this parameter on the mechanical properties. After this comparative analysis, the composition ranges C=3.30–3.40 wt-% and Si=3.75–3.80 wt-% have been selected as the most proper ones to optimise the tensile and impact properties among the high silicon ductile iron alloys. Finally, a second study was carried out to compare the tensile and fatigue properties of the optimised high silicon alloy with the corresponding ones obtained from an EN GJS 400-18-LT grade alloy with low silicon content. Although the room temperature impact values obtained from the high silicon ductile iron are lower than 6 J cm<sup>-2</sup>, the measured fatigue limit of this alloy (358 MPa) is clearly higher than the one obtained from the low silicon cast iron (170 MPa). A discussion about the benefits and advantages of the high silicon alloy is included.

**Keywords:** Ductile irons, High silicon, Mechanical properties, Fatigue properties

## Introduction

Ductile irons (DIs) exhibit an interesting range of mechanical properties depending on their microstructural features. Assuming a correct nodularity level, the mechanical properties of DIs depend almost completely on the phases (ferrite and pearlite) present in the metallic matrix. Accordingly, foundries have selected the appropriate combination of these phases in order to fit the mechanical properties required by the customers or by the corresponding standard. The competitive economic advantage of DI alloys is becoming more critical among metallic materials due to the need of low cost alloys with improved mechanical properties. Thus, efforts have been made to obtain DI alloys with high values of both tensile strength and elongation (Refs. 1–3 and references therein). An alternative is the development of austempered ductile iron (ADI) alloys where alloying methods and subsequent heat treatments are required to form a bainitic or ausferritic matrix.<sup>4–7</sup> Owing to the extra costs related to ADI, several investigations have been devoted to improve the mechanical properties obtained from as cast cast irons. In this line, silicon strengthened DI alloys become an interesting group of materials due to their good strength/elongation ratio when comparing to the standard DI grades.<sup>8</sup>

Although some high silicon DI alloys have been occasionally used in foundries so far, their application has been mainly focused to avoid the formation of carbides in small section castings. Nowadays, foundries are keen to incorporate these recently standardised grades (e.g. EN GJS 500-14 or EN GJS 600-10 according to the EN 1563:2011 European standard) to replace some conventional grades that contain both ferrite and pearlite. In addition to their mechanical properties, high silicon DI alloys usually show fully ferritic matrices with better machinability<sup>9,10</sup> and low production costs (avoidance of expensive alloying elements as Cu) compared to conventional grades. Another noteworthy effect of silicon addition is the reduction of impact resistance at a given temperature (Refs. 2 and 3 and references therein). The present work considers the influence of different silicon contents combined with high to low carbon values on mechanical response. This study is also focused to find proper chemical ranges that optimise all tensile properties leading to an optimised fully ferritic high silicon DI alloy with a remarkable fatigue limit value.

## Experimental

A group of 25 ductile iron alloys were prepared in a medium frequency induction furnace (250 Hz, 100 kW) of 100 kg in capacity. The metallic charges were composed of 45–50% low alloyed steel scrap and 55–50% low alloyed pig iron. After melting, the composition was checked and adjusted according to the required carbon and silicon contents. Special care was taken with

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Mn and P contents, which are the main contributions from the steel scrap and the pig iron used respectively. Then the melt temperature was increased to 1510–1520°C and its surface was skimmed before being transferred to a 50 kg capacity ladle for treatment with 0.6 kg (1.2 wt-% of the batch weight) of a FeSiMg alloy (grain size 2–20 mm, Si=43.54 wt-%, Mg=5.96 wt-%, Ca=0.95 wt-%, Al=0.48 wt-% and rare earth=1.08 wt-%) by the sandwich method. The FeSiMg alloy was positioned at the bottom of the ladle and then covered with steel scrap (grain size 5–15 mm) before pouring the base iron from the furnace. The treatment temperature was in the range 1480–1495°C. After completion of the reaction, a sample was taken in order to determine the chemical composition of each Mg treated batch. Then the ladle was transferred to the pouring area, where the alloys were cast in chemically bonded sand moulds. The obtained cast parts were standard keel blocks.<sup>2</sup> Inoculation treatment was carried out by adding 0.014 kg (0.20 wt-%) of a commercial inoculant (grain size 0.2–0.5 mm, Si=69.9 wt-%, Al=0.93 wt-%, Ca=1.38 wt-%, Bi=0.49 wt-% and rare earth=0.37 wt-%) into the cavity of the moulds before pouring them. Chemical compositions for all significant elements are shown in Table 1, which does not include the contribution of inoculation.

Tensile and impact experiments were made on a set of specimens machined from the bottom area of each standard keel block. A cylindrical specimen with 10 mm in gage diameter was used for tensile tests and a group of three notched samples (KV type with dimensions 10 × 10 × 55 mm) were prepared for the impact experiments at 22, –20 and –40°C. The mechanical parameters measured were the rupture stress (UTS), yield strength (Y), elongation (A) and impact energy. After tensile tests, the specimens were cut and prepared for metallographic examination. Nodularity and nodule

count ( $N$ ) were determined using quantitative image analysis software. All the samples analysed in this work showed a nodularity index higher than 90%. The fractions of ferrite ( $f^{\alpha}$ ) and pearlite ( $f^{\text{P}}$ ) were determined by comparing the microstructure obtained after etching the samples with Nital-5 etchant against standard reference microstructures.<sup>11,12</sup> Brinell hardness (HB) measurements were also made on machined samples obtained from the bottom area of the keel blocks using a 10 mm diameter sphere and a load of 3000 kg.

Fatigue tests were performed after selecting the optimised composition for the high silicon iron alloy (HSI) and thereafter, casting a group of eight keel blocks from one batch by means of the method described previously. The validation of the obtained iron alloy was made analysing its chemical composition (Table 2) and checking tensile results. A total number of 19 standard specimens (110 mm in length, 8 mm in minimum diameter and threaded ends) were machined from the bottom area of the keel blocks to build a Wohler diagram. A minimum ( $S_{\text{min}}$ ) and a maximum ( $S_{\text{max}}$ ) tensile stress were alternatively applied on the fatigue specimens with a ratio  $S_{\text{min}}/S_{\text{max}}=0.1$  and 20 Hz in frequency. The  $S_{\text{max}}$  strength was in the range 314–403 MPa. The temperature was  $21 \pm 2^\circ\text{C}$  during all the experiments. The tests were stopped after breaking the specimen or after a total number of  $4 \times 10^6$  cycles.

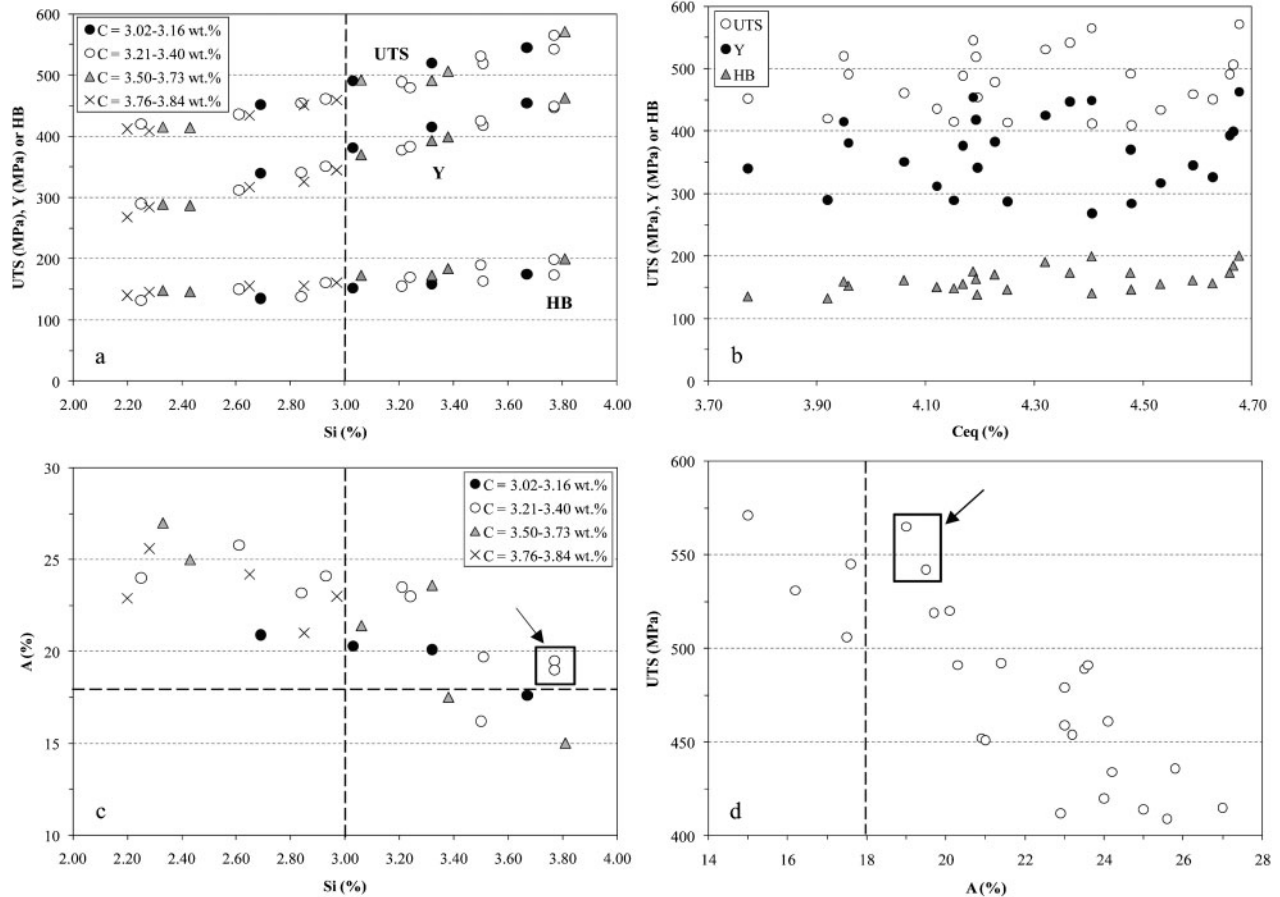
In order to compare the fatigue results with the ones obtained from a low silicon cast iron alloy (LSI) with

**Table 2 Chemical composition (wt-%) of high silicon cast iron prepared for fatigue analysis**

C	Si	Mn	P	S
3.41	3.78	0.19	0.015	0.006
Cr	Ni	Al	Cu	Mg
0.04	0.07	0.004	0.07	0.048

**Table 1 Chemical compositions (wt-%) of alloys prepared in the present work**

Alloy	C	Si	Mn	P	S	Cr	Mo	Ni	Al	Cu	Mg
1	3.11	3.03	0.06	0.016	0.005	0.030	<0.010	0.030	0.010	0.020	0.039
2	3.02	3.32	0.07	0.016	0.005	0.040	<0.010	0.040	0.010	0.020	0.051
3	3.16	3.67	0.08	0.017	0.005	0.040	<0.010	0.040	0.010	0.020	0.046
4	3.29	2.25	0.05	0.017	0.005	0.030	<0.010	0.030	0.008	<0.020	0.033
5	3.02	2.69	0.06	0.016	0.005	0.030	<0.010	0.030	0.009	0.020	0.042
6	3.40	2.84	0.05	0.017	0.005	0.029	0.003	0.032	0.006	0.018	0.039
7	3.27	3.21	0.06	0.018	0.006	0.032	0.003	0.033	0.006	0.020	0.049
8	3.21	3.51	0.06	0.018	0.007	0.033	0.004	0.034	0.006	0.022	0.060
9	3.31	3.77	0.07	0.019	0.006	0.035	0.004	0.035	0.006	0.024	0.049
10	3.50	2.33	0.10	0.019	0.009	0.033	0.004	0.072	0.007	0.052	0.039
11	3.39	2.61	0.10	0.021	0.009	0.035	0.004	0.071	0.007	0.050	0.037
12	3.24	2.93	0.11	0.021	0.009	0.036	0.005	0.073	0.008	0.052	0.037
13	3.32	3.24	0.11	0.026	0.008	0.040	0.006	0.073	0.014	0.050	0.034
14	3.34	3.50	0.07	0.027	0.009	0.042	0.005	0.039	0.009	0.027	0.035
15	3.35	3.77	0.08	0.032	0.009	0.045	0.006	0.043	0.008	0.029	0.046
16	3.79	2.20	0.06	0.026	0.008	0.038	0.004	0.038	0.007	0.022	0.054
17	3.57	2.43	0.11	0.031	0.009	0.038	0.004	0.038	0.007	0.021	0.053
18	3.83	2.85	0.05	0.020	0.008	0.032	0.004	0.034	0.007	0.020	0.047
19	3.62	3.06	0.06	0.019	0.008	0.034	0.004	0.034	0.007	0.020	0.048
20	3.72	3.38	0.06	0.019	0.008	0.036	0.004	0.035	0.007	0.022	0.047
21	3.61	3.81	0.07	0.020	0.006	0.037	0.005	0.037	0.009	0.024	0.043
22	3.84	2.28	0.06	0.016	0.006	0.035	0.004	0.036	0.008	0.016	0.038
23	3.79	2.65	0.06	0.018	0.006	0.036	0.005	0.038	0.009	0.020	0.041
24	3.76	2.97	0.07	0.019	0.007	0.039	0.007	0.040	0.009	0.023	0.042
25	3.73	3.32	0.08	0.021	0.007	0.043	0.013	0.043	0.010	0.025	0.039



1 Evolution of UTS, Y and hardness *a* with Si content and *b* with Ceq content; *c* evolution of elongation at rupture with Si content and *d* UTS versus A plot for prepared cast irons

high impact properties, a set of 9 EN GJS 400-18-LT grade keel blocks were produced following an analogous methodology to the one described above. Again the chemical composition (Table 3) and the tensile properties of this LSI alloy were checked. A group of 28 fatigue specimens were machined from the keel blocks and then

Table 3 Chemical composition (wt.-%) of EN GJS 400-18-LT cast iron prepared for fatigue analysis

C	Si	Mn	P	S
3-69	2-18	0-14	0-027	0-006
Cr	Ni	Al	Cu	Mg
0-03	0-027	0-009	0-06	0-038

used to build the analogous Wohler diagram following the test conditions mentioned above. In this case, the  $S_{max}$  strength was in the range 170–200 MPa.

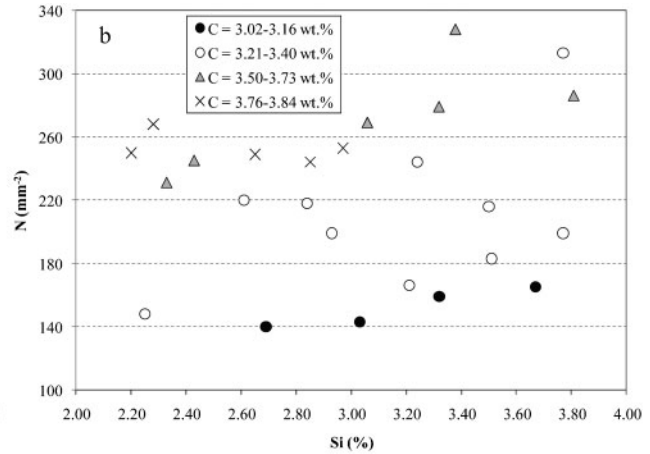
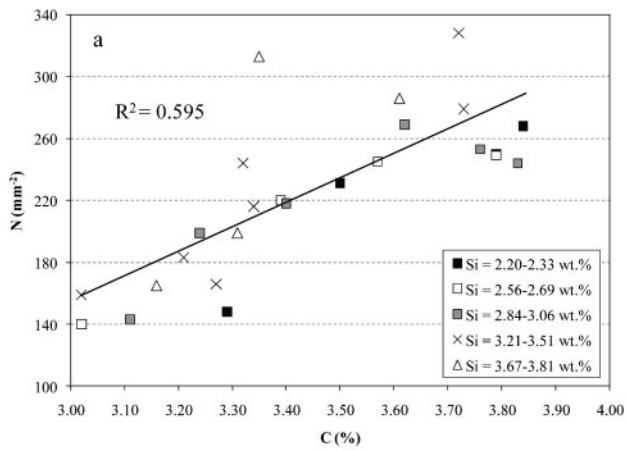
## Results and discussion

Structural data obtained from the whole set of alloys prepared in the present work are shown in Table 4. It is observed that six alloys have not a fully ferritic matrix and their silicon content is lower than 3.00 wt.-% but alloy 1. As expected, high nodule count and high carbon contents appear to favour a fully ferritic matrix.

Figure 1a and b shows the evolution of UTS, Y and HB as a function of silicon and carbon equivalent Ceq (calculated as  $\%C + 0.28\%Si$ , wt.-%) contents for all

Table 4 Results obtained from metallographic inspections made on prepared alloys

Alloy	Si/wt.-%	$N/mm^{-2}$	$f^{\alpha}$	$f^P$	Alloy	Si/wt.-%	$N/mm^{-2}$	$f^{\alpha}$	$f^P$
1	3-03	141	0-99	0-01	14	3-50	216	1-00	0
2	3-32	164	1-00	0	15	3-77	313	1-00	0
3	3-67	165	1-00	0	16	2-20	248	0-96	0-04
4	2-25	149	0-89	0-11	17	2-43	225	0-95	0-05
5	2-69	136	0-97	0-03	18	2-85	248	1-00	0
6	2-84	162	0-99	0-01	19	3-06	291	1-00	0
7	3-21	146	1-00	0	20	3-38	321	1-00	0
8	3-51	175	1-00	0	21	3-81	323	1-00	0
9	3-77	166	1-00	0	22	2-28	275	1-00	0
10	2-33	307	1-00	0	23	2-65	262	1-00	0
11	2-61	246	1-00	0	24	2-97	265	1-00	0
12	2-93	214	1-00	0	25	3-32	267	1-00	0
13	3-24	241	1-00	0					



## 2 Nodule count evolution with *a* carbon and *b* silicon contents

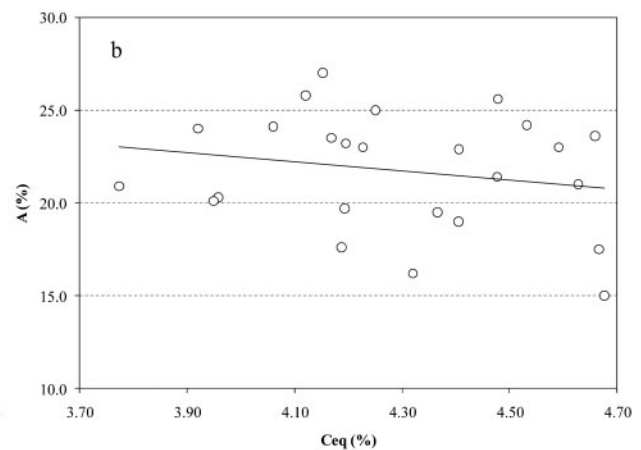
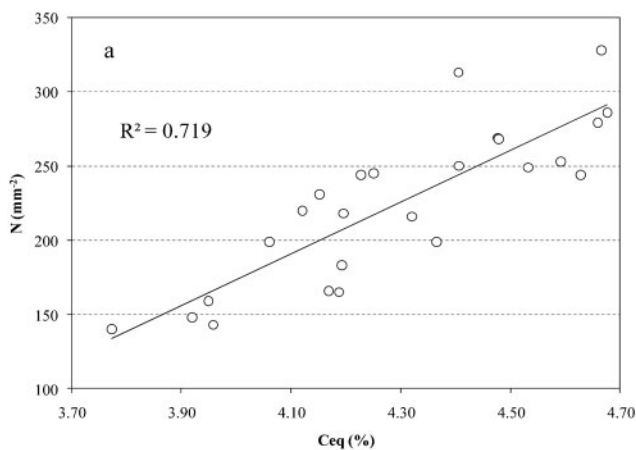
alloys prepared in this work. As expected from literature,<sup>8,9,13</sup> it is observed an increase of UTS, Y and HB parameters when increasing the silicon content in the alloy (Fig. 1a). The strengthening effect is much weaker and scattered when increasing the carbon equivalent as seen in Fig. 1b, so the influence of carbon content on these mechanical properties does not seem to be potent. Further plots to obtain a direct correlation between carbon contents and UTS, Y and HB for a given silicon range confirmed this trend. Here it is also necessary to stress that alloys with the highest silicon contents were prepared using the lowest carbon content range to avoid the formation of degenerated graphite particles<sup>14</sup> and/or flotation phenomena during solidification.

Elongation data included in Fig. 1c show the negative effect of silicon on this parameter in accordance to the opposite effect obtained on UTS, Y and HB. A relatively high scattering has been obtained in elongation due to the potential influence of material irregularities (surface quality of specimens, undetected microshrinkages or small inclusions, etc.). The minimum elongation values vary from 15 to 18% for the high silicon alloys with quite different carbon contents and with UTS values ranging from 506 to 571 MPa. This result is noteworthy as the standard ferrite-pearlite cast irons with UTS values around 550 MPa do not usually achieve elongations higher than 10–12%. All the alloys prepared in the present work with silicon contents higher

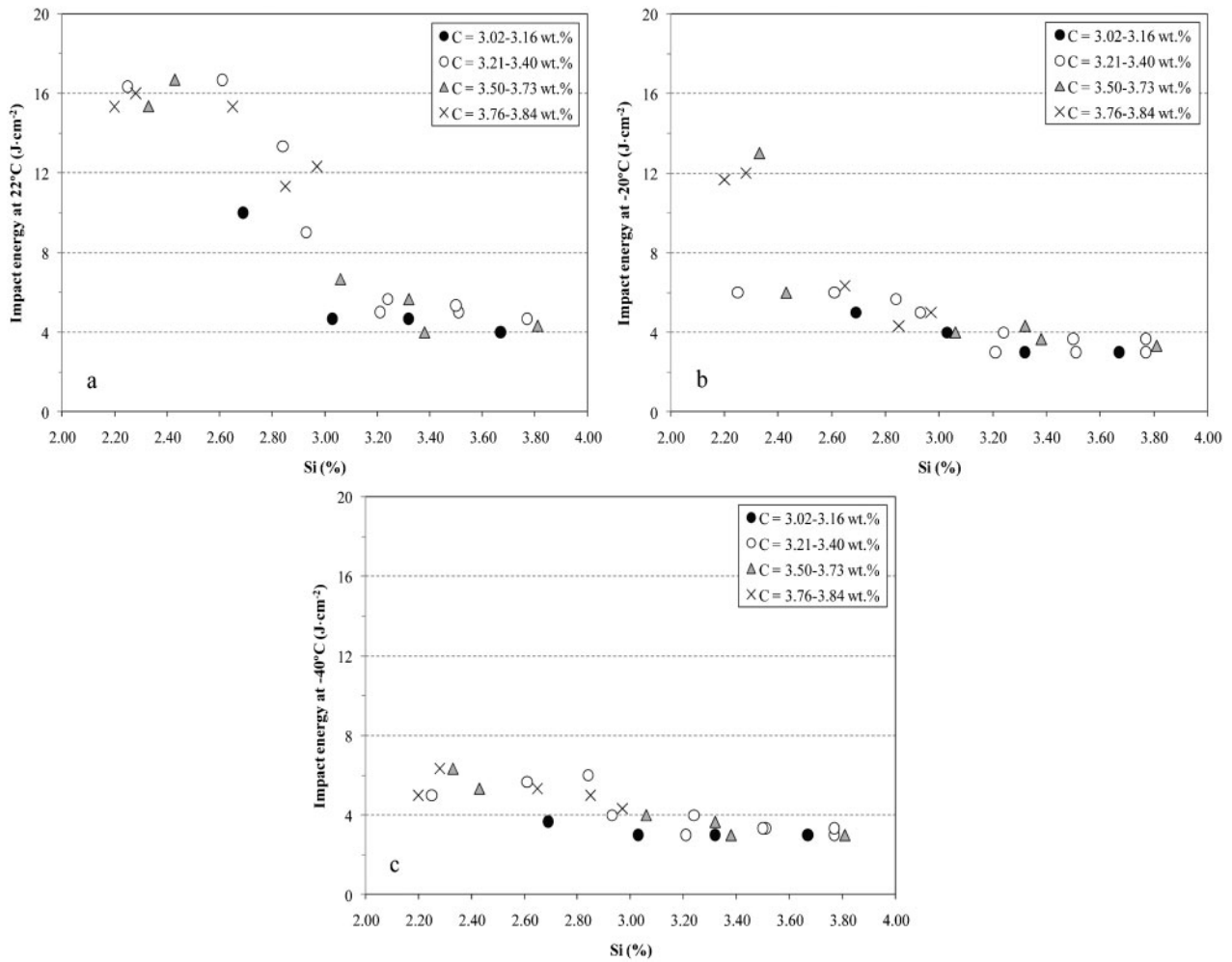
than 3.03 wt-% showed fully ferritic matrices (Table 4) and accordingly, the ductility values are higher than the ones found in other ductile irons, which also contain important amounts of pearlite.

A minimum limit of 18% in elongation has been adopted to optimise the mechanical properties of the prepared cast irons. On the other hand, a minimum silicon content of 3.00 wt-% has been adopted for maximising UTS and Y values according to Fig. 1a. These two conditions are illustrated by means of dotted horizontal and vertical lines in Fig. 1c. Most of the alloys into the upper right corner of the graph have silicon contents higher than 3.20 wt-% and they belong to the group of irons manufactured with 3.21–3.40 wt-% in carbon, though the direct effect of this latter element on tensile properties has been shown to be unclear. More concisely, the two alloys marked in Fig. 1c by means of a solid square (Si=3.77 wt-%) show elongation values slightly lower than 20% while their UTS values are in the range 542–565 MPa (Fig. 1d).

According to the data shown in Fig. 1, elongation becomes the most critical tensile parameter to be optimised when increasing silicon content in the prepared cast irons. Therefore, it seemed of interest to obtain a more detailed understanding about the effect of silicon and carbon on nodule count and about the outcome of this structural feature on elongation. Figures 2 and 3 show the correlations obtained regarding these two



## 3 *a* Nodule count versus Ceq and *b* elongation versus Ceq. Only data on ferritic alloys was selected.



4 Evolution of impact energy at a 22°C, b -20°C and c -40°C for prepared cast irons

aspects. Only data from fully ferritic cast irons were used in Fig. 3 to avoid the effect of minor amounts of pearlite on A values.

As seen in Fig. 2a, increasing carbon content increases nodule count for the entire silicon range studied in this work. According to Fig. 2b, any effect of silicon on N could hardly be observed due to the scattering of the data. Figure 3 shows the combined effect of these two elements, expressed as Ceq, on nodule count and elongation. When comparing Figs. 3a and 2a, it is observed that the positive correlation obtained for Ceq is significantly better than that detected for carbon. This fact shows that silicon is acting on N parameter in some way even if this effect could not be evidenced in Fig. 2b.

It is seen in Fig. 3b that the negative effect on A exhibited by silicon in Fig. 1c becomes less critical when plotting it versus Ceq. In order to get a quantitative view of the effect of N and composition on A, a statistical analysis was performed using JMP software with the data for ferritic alloys only. From this analysis, a model expressing the selected output variable as a first order polynomial was obtained (equation (1)) with a  $R^2$  coefficient of 0.82

$$A (\%) = 27.4 + 3.15w_C - 5.58w_{Si} + 69.2w_{Mn} - 0.02N \quad (1)$$

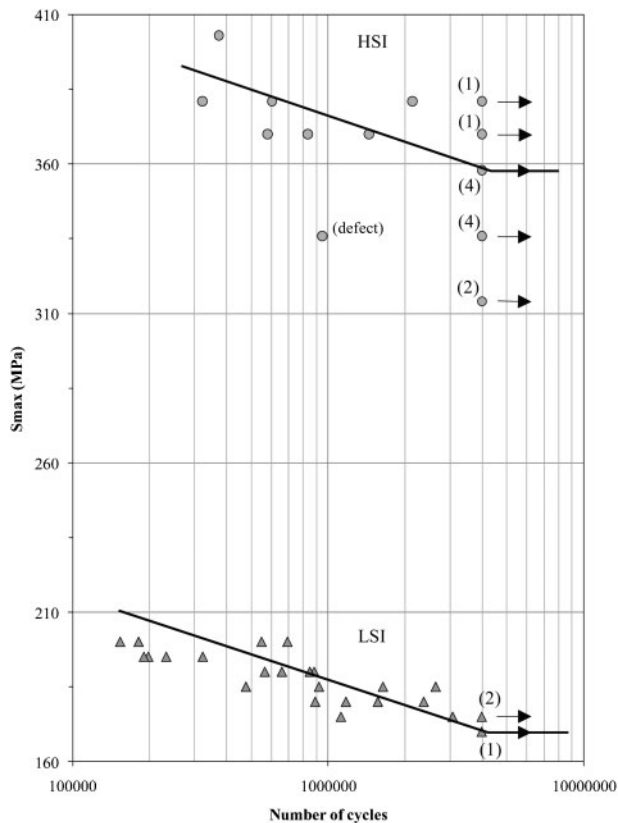
In this expression  $w_C$ ,  $w_{Si}$  and  $w_{Mn}$  correspond to carbon, silicon and manganese contents. The significance

of the coefficients for silicon and manganese contents and of the constant was very high while it was lower for the carbon content and N. The positive effect of carbon content appears opposite to the negative effect of N. This negative effect of N does not appear in agreement with the reported negative evolution of A when increasing casting sections,<sup>15</sup> which may be an artefact due to a limited number of available data points. The strong negative effect of silicon is confirmed, while the positive effect of manganese seems not to have been reported before and is of great interest: in alloys containing enough silicon to be fully ferritic, manganese could lead to some improvement of the elongation at rupture.

Figure 4 shows the evolution of impact properties when increasing the silicon content at three different temperatures. In all cases, higher silicon contents reduce the measured impact energy for rupture as this element strongly increases the ductile to brittle temperature.<sup>2,16</sup>

A maximisation of UTS and Y parameters leads to select the highest silicon contents while keeping the maximum value of elongation. Thus, a high silicon range (3.75–3.80 wt.%) combined with an intermediate range for carbon (3.30–3.40 wt.%) seems to be adequate as it has been stated previously in relation with Fig. 1c and d. The choice of an optimised high silicon range as 3.75–3.80 wt.% leads to impact values lower than 6 J cm<sup>-2</sup> at room temperature according to the brittle fractures found in both tensile and impact specimens.





**5 Fatigue response of HSI (upper data) and LSI (lower data) alloys**

Although this impact response is not accepted in several applications for ferritic cast irons with toughness requirements, e.g. wind mills and automotive, it seems to be worth studying the fatigue response of the optimised HSI in comparison to the LSI EN GJS 400-18-LT standard grade commonly used for such demands. For such purpose, tensile properties of both cast irons (*see* Tables 2 and 3 for their compositions) were determined in a first step to characterise their yield strength responses. Additional metallographic characterisations made on the two tested tensile specimens showed fully ferritic matrices and correct nodularities (>90%). Table 5 lists the results obtained from the tensile tests and the nodule count values measured on both specimens (areas close to the fracture surfaces).

Figure 5 shows a Wohler diagram that was plotted comparing the fatigue results from the HSI and LSI alloys. In this figure, numbers between brackets indicate the amount of specimens tested for each  $S_{max}$  value when no cracking was obtained. The scattering found in both sets of data has been assigned to material heterogeneities that are present in fatigue specimens. In this context, the low number of cycles achieved for one of the specimens tested under  $S_{max}=336$  MPa

**Table 5 Tensile results and nodule count values obtained on prepared HSI and LSI cast irons**

Alloy	UTS/MPa	Y/MPa	A/%	N/mm <sup>-2</sup>
HSI	549	448	17.6	275
LSI	434	247	20.1	209

strength (Fig. 5) is due to cross inclusions detected on the fracture surfaces.

The fatigue limit obtained for the HSI alloy (358 MPa) is much higher than the one from LSI alloy (170 MPa). Thus, it is expected that the former material needs to be affected by much bigger stress efforts to nucleate cracks and to promote any kind of tearing when comparing to LSI alloy. It has been shown in the present work that impact properties of the HSI alloy are low, though its fatigue response is clearly better than the one exhibited by the LSI alloy.

Therefore, it is worthy to discuss about the relevance of impact properties as a representative indicator of real efforts undergone by wind mill components because such service conditions do not seem to be realistic. Similarly, it seems also questionable to use cast irons with low fatigue limit and with high impact properties for manufacturing cast parts for automotive components among others applications. On the contrary, a more resistant and ductile material such the HSI alloy, though brittle at low temperature, could have an advantage against a cast iron with a low cracking risk, but easy to deform under comparatively low stresses.

## Conclusions

A group of 25 different as cast ductile iron alloys were prepared and their structural and mechanical properties comparatively analysed in order to find chemical ranges to prepare high silicon alloys with optimised tensile and impact properties. As expected, silicon contents higher than 3% increases UTS, Y and hardness while having a negative effect on elongation and impact properties. On the other hand, the effect of carbon on mechanical properties has shown to be weak. The composition ranges C=3.30–3.40 wt-% and Si=3.75–3.80 wt-% have been chosen so as to achieve tensile strengths higher than 540 MPa while keeping noteworthy elongation values (15–18%), which are clearly better than those exhibited by the ordinary EN GJS 500-7 grade. An additional advantage of these high silicon ductile irons is their fully ferritic matrix.

The optimised high silicon alloys found in this work have shown impact values lower than 6 J cm<sup>-2</sup> at room temperature. This fact has been traditionally considered as a negative aspect when using ductile irons in several applications with toughness requirements. In this sense, it is assumed that a low impact response would reduce the life span of castings due to crack propagation. However, the prepared high silicon cast iron alloy showed a high fatigue limit (358 MPa), together with an important ductility (17.6% of elongation). A comparative statement about the importance of the fatigue property against the impact response exhibited by the classic EN GJS 400-18-LT grade has been also made to support this argument.

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