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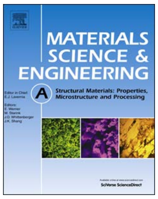

Effects of high silicon contents on graphite morphology and room temperature mechanical properties of as-cast ferritic ductile cast irons. Part II – Mechanical properties

Rodolfo González-Martínez[a], Urko de la Torre[a], André Ebel[b], Jacques Lacaze[b], Jon Sertucha[a,*]

[a] Investigación y Desarrollo de Procesos Metalúrgicos, IK4-Azterlan, Aliendalde Auzunea 6, E-48200 Durango, Bizkaia, Spain
[b] CIRIMAT, Université de Toulouse, BP 44362, F-31030 Toulouse, France

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ABSTRACT

In this second part of the investigation, room temperature mechanical properties and hardness evolution of cast irons with silicon contents ranging from 2.29 wt% to 9.12 wt% have been studied and related to structural results from the first part. Increasing silicon content increases ultimate tensile strength and yield stress until a maximum value of 719 MPa at around 5.0 – 5.2 wt% silicon for the former and 628 MPa at 5.2 – 5.4 wt% silicon for the latter. Brinell hardness remains increasing with silicon content with a maximum value of 396 at 9.12 wt% silicon. Elongation at rupture shows an opposite evolution and gradually decreases to zero at 5.3 wt% silicon. This evolution is related to chemical ordering of the ferritic matrix (embrittlement effect). Chunky graphite shows apparently no significant effect on the ultimate tensile strength and yield strength in cast irons with silicon contents higher than 4.0 wt%. However, it has a negative effect on elongation. This result contrasts with the negative effect of chunky graphite on mechanical properties of ductile irons reported in the literature for alloys with silicon contents lower than 3 wt%. It is suggested that this difference is due to the matrix strengthening effect of high silicon contents which overtakes the detrimental effect of chunky graphite. This study suggests that cast irons with silicon content as high as 5.0 wt% could be considered for industrial applications when high resistance and some ductility are requested.

1. Introduction

The interest for increasing silicon content in cast irons for better mechanical properties and higher corrosion resistance has been recognized for long as reviewed by Fairhurst and Röhrig [1]. This has led to the development of the SiMo spheroidal graphite cast irons and there is still strong interest in further improving these latter alloys as shown with recent works [2–4]. Although further increase in silicon content is detrimental for impact properties of cast irons [5], there is a renewed interest for such high-silicon alloys. This is because they show a good combination of tensile properties, a homogeneous microstructure and an expected excellent machinability with low tools wear when compared to conventional ferritic or ferritic-pearlitic alloys at similar levels of tensile strength [3,6–8]. Also, high silicon contents improve the corrosion resistance of cast irons against various environments [9,10]. However structural characteristics and mechanical properties of high-silicon ferritic cast irons are still unclear for the highest silicon contents, i.e. above 3.5 – 4.0 wt%. These uncertainties are contributing to make it difficult the development of this group of ductile iron alloys for different applications as customers commonly require highly controlled and low scattered casting properties.

Solid solution hardening with silicon is well-known in ferritic cast irons and is associated with increased hardness, rupture stress and yield strength while elongation at rupture is progressively reduced [6,8,11,12]. Impact resistance of ferritic ductile irons sharply decreases at increasing silicon content [13–16] though ductility is not reduced as much as it is commonly observed in ductile irons with increasing pearlite contents. When silicon content is further increased above most common practice, Stets et al. [12] and Glavas et al. [17] reported the existence of a maximum value for tensile strength and for yield strength at 4.2 – 4.3 wt% silicon in agreement with previous fragmentary knowledge [1]. Above this critical content they reported that both properties rapidly decrease. As reviewed by Wittig and Frommeyer [18], there is a similar decrease in ductility in soft magnetic steels at about 4–5 wt% silicon. There is thus a clear interest in further studying this transition in cast irons and making it clear if the sharp drop in mechanical properties in this range of silicon contents has similar characteristics as those known for silicon steels.

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* Corresponding author.
E-mail address: jsertucha@azterlan.es (J. Sertucha).

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One of the reasons that could make difficult the analysis of the effect of silicon on mechanical testing is that this element is known to favor graphite degeneracy, i.e. decrease in nodularity and also appearance of chunky graphite [12,19–24]. Besides the influence on the matrix constituents, the nodule count, the size and the roundness of the graphite particles are determining factors with respect to mechanical properties [11,25–31]. For alloys with silicon content lower than 3 wt%, it has been reported that chunky graphite decreases elongation at rupture and ultimate tensile strength without affecting yield strength [25,32,33]. However, the most problematic effect for engineering applications is certainly that chunky graphite does also decrease fatigue resistance [25,34–39].

In the first part of this study was presented the microstructure of 30 ferritic cast irons containing 3.88–6.11 wt% silicon, and one alloy at 9.12 wt% silicon. Chunky graphite formation could be observed and antimony was added to some of these alloys to limit the extent of this graphite degeneracy. An index denoted Ω_{Si} that is based on the content of the alloys in silicon, cerium, magnesium and antimony was proposed that shows a critical value around 7 wt%, over which the amount of chunky graphite increases steadily from zero. In this second part of the study, we report room temperature hardness and tensile properties of the alloys presented in part 1 and also from an additional set of 21 high silicon cast irons prepared similarly for reproducibility check in the highest silicon content range. The present data is also complemented with previous results on nodular cast irons with lower content in silicon, and is compared to literature data. In the discussion of these results, emphasis is put on the role of silicon on hardening the matrix and on the impact of chunky graphite.

2. Experimental details

In this second part of the study, the room temperature mechanical properties of the 31 ductile iron alloys presented in the first part and of the 21 additional alloys are characterized. These additional alloys were prepared following the same procedure as that described in the first part of this work with some antimony addition to decrease chunky graphite formation. Data from the 25 ferritic alloys reported by de la Torre et al. [8] and from the three Ni-free ferritic alloys reported by Lacaze et al. [15] have been also considered in the present study. The tensile parameters, ultimate tensile stress (UTS), yield strength (Y) and elongation (A), were measured using a Zwick Z250 tensile testing equipment at a controlled strain rate of 0.90 mm/min in the range where Y was determined. This rate was then increased to 24.12 mm/min to determine UTS and A according to the standard ISO 6892-1 A224. Brinell hardness (HBW) was measured with a Instron Wolpert apparatus with a 10 mm diameter sphere and a load of 3000 kg. Vickers micro-hardness (HV) measurements were performed using a Leica WMHT Auto workstation with a diamond pyramid and loads of 10 and 5 g for 10 and 5 s, respectively.

Scanning electron microscopy (SEM) characterization was carried out on the fracture surface of a few representative alloys using a Zeiss Ultra Plus microscope.

3. Results

Table 1 shows tensile tests and Brinell hardness values together with chunky graphite fractions and the relevant amounts of significant elements for the same 31 alloys than in the first part of this work. All alloys were fully ferritic but alloy #26 which showed 3 – 5% pearlite because of its low Si content. Table 2 lists the tensile mechanical properties and composition of the 21 additional alloys. Values of the Ω_{Si} parameter that was defined in the first part of this study has been also included in Tables 1 and 2 to evaluate the risk of chunky graphite appearance.

Table 1
Tensile test results (UTS, Y and A), hardness values HBW, fraction of chunky graphite f_{CHG}^{A}(see part I), and carbon, silicon, antimony and Ω_{Si} contents of the same 31 alloys as in part I of this study.

Alloy	UTS (MPa)	Y (MPa)	A (%)	HBW	f_{CHG}^{A}	C (wt%)	Si (wt%)	Sb (wt%)	Ω_{Si} (wt%)
1	541	442	10.8	200	0.19	3.15	3.88	< 0.0005	10.15
2	566	470	8.7	208	0.34	3.16	4.11	< 0.0005	10.09
3	595	502	6.2	225	0.31	3.16	4.34	< 0.0005	10.88
4	614	520	7.2	225	0.39	3.10	4.45	< 0.0005	10.96
5	637	544	3.9	234	0.34	3.08	4.66	< 0.0005	11.10
6	565	456	16.7	203	0.00	3.13	3.94	0.0038	7.15
7	587	485	10.2	217	0.30	3.13	4.25	< 0.0005	10.66
8	631	516	10.9	228	0.04	3.10	4.45	0.0037	8.01
9	673	578	2.2	253	0.18	2.93	4.93	0.0028	9.46
10	701	592	2.5	265	0.02	2.93	5.11	0.0035	8.38
11	671	549	4.8	242	0.00	2.95	4.84	0.0040	7.41
12	659	577	1.4	256	0.04	2.91	5.04	0.0036	8.19
13	679	609	1.0	271	0.23	2.69	5.32	0.0040	8.70
14	526	0	0.0	282	0.03	2.72	5.55	0.0044	7.83
15	482	0	0.0	295	0.15	2.75	5.70	0.0039	9.70
16	681	603	2.1	263	0.04	2.71	5.15	0.0031	10.07
17	605	0	0.2	265	0.21	2.65	5.42	0.0031	9.93
18	661	625	0.5	269	0.15	2.75	5.36	0.0034	9.79
19	536	0	0.0	313	0.26	2.76	5.39	0.0029	10.42
20	397	0	0.0	285	0.33	2.77	5.56	0.0025	9.96
21	0	0	0.0	315	0.65	2.64	6.11	< 0.0005	13.29
22	0	0	0.0	310	0.11	2.71	6.14	0.0042	10.16
23	615	517	10.1	225	0.43	2.96	4.61	< 0.0005	10.89
24	636	518	15.5	220	0.00	2.90	4.60	0.0059	5.95
25	706	628	1.3	266	0.06	2.31	5.21	< 0.0005	11.87
26	417	289	22.3	146	0.00	3.67	2.29	< 0.0005	8.14
27	481	0	0.0	295	0.88	2.26	5.75	< 0.0005	11.82
28	0	0	0.0	396	0.17	2.41	9.12	< 0.0005	14.44
29	642	517	14.0	221	–	2.85	4.63	< 0.0005	10.89
30	671	548	8.2	232	0.14	2.93	4.74	< 0.0005	11.53
31	676	563	6.3	240	0.57	2.95	4.87	< 0.0005	11.40

Table 2
Tensile test results (UTS, Y and A), carbon, silicon and Sb contents and value of Ω_{Si} for the 21 additional alloys.

Alloy	UTS (MPa)	Y (MPa)	A (%)	C (wt%)	Si (wt%)	Sb (wt%)	Mg (wt%)	Ce (wt%)	Ω_{Si} (wt%)
1-2	719	576	6.2	2.91	4.98	0.0025	0.037	0.0060	9.25
2-2	695	592	2.0	2.85	5.20	0.0032	0.034	0.0055	8.46
3-2	709	585	3.0	2.85	5.12	0.0041	0.035	0.0060	8.00
4-2	651	605	0.6	2.60	5.27	0.0047	0.031	0.0055	7.11
5-2	681	590	1.5	2.71	5.24	0.0035	0.038	0.0071	9.24
6-2	622	613	0.2	2.62	5.24	0.0033	0.033	0.0074	8.91
7-2	671	617	0.7	2.69	5.42	0.0037	0.036	0.0070	9.02
8-2	708	574	5.4	2.88	4.93	0.0028	0.037	0.0057	8.88
9-2	707	595	2.5	2.89	5.11	0.0030	0.036	0.0054	8.71
10-2	687	583	2.2	2.86	5.14	0.0038	0.033	0.0056	7.89
11-2	681	607	1.1	2.66	5.32	0.0045	0.029	0.0051	6.95
12-2	699	597	2.1	2.69	5.15	0.0033	0.034	0.0070	8.81
13-2	681	617	0.9	2.59	5.29	0.0032	0.034	0.0068	8.96
14-2	651	623	0.4	2.64	5.36	0.0039	0.033	0.0066	8.35
15-2	705	558	6.4	2.88	4.99	0.0027	0.037	0.0060	9.11
16-2	672	577	1.7	2.82	5.24	0.0032	0.034	0.0057	8.57
17-2	688	559	4.5	2.86	4.84	0.0042	0.035	0.0058	7.59
18-2	467	0	0.0	2.59	5.34	0.0049	0.033	0.0057	7.32
19-2	648	584	0.9	2.70	5.23	0.0035	0.037	0.0071	9.12
20-2	617	602	0.3	2.67	5.35	0.0037	0.036	0.0068	8.89
21-2	603	0	0.0	2.60	5.38	0.0035	0.035	0.0076	9.20

Fig. 1 shows the tensile strain-stress curves recorded on five alloys with silicon content in between 4.84 wt% and 5.70 wt%. For readability, the curves have been shifted along the abscissa as indicated between brackets. In the high silicon range illustrated in Fig. 1, it is observed that silicon does not significantly affect the Young's modulus, i.e. the slope of the curves in the elastic or pseudo-elastic regime. Increasing the silicon content does increase the UTS value up to 5.21 wt% (see alloy #25 in Table 1) while it decreases at higher silicon contents. In Fig. 1, this decrease is clearly related to a marked reduction of A up to a point where there is no plastic deformation for the highest silicon