Low temperature impact strength of heavy section ductile iron castings: effects of microstructure and chemical composition

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Abstract: A foundry research project has been recently initiated at RTIT in order to better understand the fabrication of as-cast heavy section DI parts meeting high impact energy requirements at low temperatures. The experimental castings have the following dimensions 180 mm x 180 mm x 190 mm. The achieved as-cast Charpy impact strengths were as follows: 17 J (RT), 16 J (-20°C) and 11 J (-40°C). The foundry process, the chemical composition and the microstructure of this experimental casting are compared to the ones of various examples in order to show the detrimental effects of residual elements, microshrinkage and microcarbide on the impact properties. Finally, quality index empirical models (based on casting chemical compositions) are used to analyse the impact tests results. This paper illustrates that an adequate nodule count can contribute to reducing the detrimental effects of the residual elements and microsegregation.

Key words: heavy section ductile iron casting; as-cast microstructure; low temperature impact strength; quality index; ferritic ductile iron

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Over the last ten years period, the needs for heavy section ductile iron castings (HSDIC) have increased in the wind energy, gas & water energy, mine and cement industry sectors. For instance, the global installed wind turbines capacity has increased from about 10,000 to 127,000 MW. These wind turbines require several HSDIC (15 to 25 t of ductile iron per MW with castings weighing from 0.5 to 30 t). Emergent sectors such as tidal energy will also increase the demand for those castings in the near future. When installed in a cold environment, the HSDIC must meet low temperature impact properties as well as static tensile, yield and elongation minimum values. The impact strength requirement is typically 12 J at -20℃ or 10 J for the thickest section size castings, accordingly to DIN EN 1563 Standard. A ferritizing anneal can be utilized to attain these properties. However, this is costly and impractical when castings of large mass and dimensions are considered. A more economical method is to achieve the properties under the as-cast condition.

The first section of the paper presents static mechanical properties and impact strength results obtained for HSDIC as described in the literature.

The results section is divided in two parts. First, the microstructure and impact strength of samples provided by two industrial HSDIC foundries are presented. The second section summarizes the recent foundry research project conducted at RTIT in order to better understand the fabrication of HSDIC meeting high impact energy requirements at low temperature. The chemical compositions and detailed microstructure correlated to the impact strength of these castings are among the information discussed.

Finally, quality index empirical models (based on casting chemical compositions and independent references) are used to analyse the impact tests results.

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1 Literature review

1.1 Static mechanical properties

The Ductile Iron Society published in 1977 a comprehensive report entitled "Factors Affecting Optimum Properties in Heavy Section Ductile Iron"[1]. In this document, the reported mechanical properties did not include Charpy impact strength. However, they produced 37 cubic castings (24 × 24 × 24 cm^3) and investigated the effects of different factors in order to improve the as-cast tensile properties. Their first conclusion was: "The slower solidification rate obtained in the heavy sections makes the iron susceptible to loss of quality because of degenerated graphite, reduced nodule count and, in some cases, free carbides…"

In order to counteract the effect of section size and holding time, it was suggested to use post-inoculation. Another observation was the importance of balancing deleterious elements (such as Sb or Pb) with rare earths (Ce). The combined effect of these elements provided good nodularity with mostly type I and II graphite (ASTM-A247). Table 1 presents the characteristics of the castings having the best microstructure produced in this research program.

In 1985, Gagné and Argo[2] studied the occurrence of chunky graphite in cylindrical HSDIC (Φ=180 mm). It was proposed that the use of low carbon equivalent (< 4.2) was effective in the elimination of chunk graphite. The use of a pouring temperature above 1,370℃ was also recommended.

The beneficial effect of antimony (~ 40 ppm) to inhibit the formation of chunk graphite was confirmed in heats having a CE ~ 4.4–4.8. For this low Sb percentage, the matrix was fully ferritic and the nodule count was in the range of 140 N/mm^2 in the thermal center of the casting.

An extensive literature review by Javaid and Loper[3] described the production parameters (melt treatment and composition, effect of rare earth and subversive elements) that optimize the microstructure of HSDIC. In their concluding remarks, they specified that the amount of rare earth (Ce, La) added should be 1.5 times the total amount of subversive elements (Sb, Bi, As, Pb, Te, Ti) . In the final composition of the iron, the analysed ratio was reduced to 1. They also recommended having a minimum of 60–70 Nod/mm^2 in order to achieve acceptable structure. To reach this nodule count, effective post inoculation, multi stage inoculation and the reduction of the melt handling time was strongly recommended.

One of the latest papers published by Lacaze[4] quantified the effect of (Sb + Ce) and carbon equivalent on the chunk graphite formation. The experimental casting was a cube of 30 × 30 × 30 cm^3. The authors measured the cooling curves (CC) in the thermal center of the casting and tried to correlate the microstructure to the typical arrest points of the CCs. They produced chunk graphite free castings for chemical compositions and nodule counts reported in Table 2. This is another example of the importance of using RE and subversive elements in combination. However, the ratio (Ce + La)/ Sb is 0.65 which is slightly different from Javaid and Loper suggestion (ratio ~1–1.5).

Table 1: Composition and microstructure at the center of cubic casting (24 × 24 × 24 cm^3)[1]

#	CE	C (%)	Si (%)	Mn (%)	P (%)	S (%)	Mg (%)	Intercellular (%)	Other	Nod/mm^2	P (%)	UTS (MPa)	YS (MPa)	El (%)
1	4.54	3.6	2.83	0.31	0.023	0.014	0.054	1	Trace chunk	110	4	440	324	24
2	4.55	3.67	2.63	0.33	0.02	0.002	0.04	2	Nil	75	7	422	280	21

1. Mg plunging technique, 0.9%Si inoculated in the pouring ladle with FeSi Foundry Grade with Ca and Al.
2. Holding time in the furnace for 30 min, post inoculated with pellets in the runner, 0.14%Cu, 0.115%Cr, 0.21%Ni, 0.001%Ce.

Table 2: Chemical composition (wt.%) and microstructure characteristics of chunk free graphite HSDIC[4]

C	Si	P	S	Cu	Mg	Ce	La	Sb	CE(%)	Nod/mm^2	Flotation
3.82	2.41	0.035	NA	0.03	0.055	0.0028	0.0024	0.008	4.49	100	yes
3.13	2.08	0.030	0.002	0.02	0.042	0.0026	0.0021	0.008	3.71	75	no

1.2 Charpy impact strength of HSDIC

The results of the DIS research [1] can be compared to the properties listed in Table 3. This table presents a summary of the requirements described in DIN 1563-2003 which is the reference European standard for heavy section castings as those for wind mill castings. The impact properties were not tested in the DIS research but the elongation, the tensile and the yield strengths of Samples 1 and 2 (Table 1) exceed the requirements in bold italic characters in Table 3. However, since the Si content was > 2.5% in these tests, it is expected that the impact strength at low temperature would be lower than that of the DIN requirement. The adverse effect of Si on

Table 3: Summary of requirements for cast-on sample as per standard DIN 1563-2003-02[5]

Material designation symbol	Relevant wall thickness, *t* (mm)	Min. impact mean 3 tests (J)	Min. impact Individual (J)	Min. tensile strength (MPa)	Min. 0.2% proof stress (MPa)	El (%)
EN-GJS-350-22U-LT Impact at - 40 ± 2℃	< 30	12	9	350	220	22
	30 < *t* ≤ 60	12	9	330	210	18
	60 < *t* ≤ 200	10	7	***320***	***200***	***15***
EN-GJS-400-18U-LT Impact at - 20 ± 2℃	< 30	12	9	400	240	18
	30 < *t* ≤60	12	9	390	230	15
	60 < *t* ≤200	10	7	***370***	***220***	***12***

impact property was documented in many references including The Sorelmetal Book of Ductile Iron [6].

In his review on the properties of large section nodular iron castings, Palmer [7] illustrated the detrimental effect of increased section size (modulus) on the ductile-to-brittle transition temperature as well as on the upper-shelf energy. The results were those from the experimental work of Jolley and Gilbert [8]. Palmer showed that the negative effects of large moduli castings were influenced by the residual element levels in those castings. The effects were observed even if the irons were annealed. The chemical compositions are given in Table 4 and the corresponding Charpy impact results are presented in Table 5. It was observed that even for a "Pure" and "Normal" HSDIC both with low Si, the impact strength at - 40℃ of a 300 mm section size casting, was inferior to 10 J, which is the minimum requirement listed in Table 3.

The aim of this literature review was to select the appropriate chemical composition and foundry process in order to produce as-cast high impact strength HSDIC. Unfortunately, it was not possible to find in the literature an extensive description of the metallic charge/processing method/chemical composition/microstructure that correspond to high impact strength ferritic as-cast ductile iron.

Table 4: Chemical compositions (wt.%) of DI in the work of Jolley & Gilbert [8]

Iron	C	Si	Mn	S	P	Ni	Cr
Normal	3.50	2.00	0.37	0.018	0.028	0.78	0.10
Pure	3.53	1.95	<0.01	0.015	0.016	0.76	<0.01

Table 5: Charpy impact strength of DI in the Work of Jolley & Gilbert [8]

	Size	Impact strength (J)	
		- 20 °C	- 40°C
Normal	44 mm	14	9
	300 mm	4	3
Pure	44 mm	15	10
	300 mm	11	7

2 Experimental details

2.1 Examples of industrial HSDIC

(a) Case Analysis A

This first example was provided by a European foundry. The target material grade was the EN-GJS-400-18U-LT. The typical as-cast microstructure of the cast-on sample (25 mm × 25 mm × 125 mm) is presented in Fig. 1. Note that the microstructure was taken at the geometrical center of the sample. Few dross defects were also observed as shown in Fig. 2.

The image analysis results are reported in Table 6. The chemical composition of the sample is presented in Table 7 and the Charpy impact test results, in Table 8.

The main problem encountered with this DI was its low upper-shelf energy which was close to the -20℃ requirement. It is normally expected to obtain 16 –18 J at room temperature for a good quality ferritic DI. However, the ductile-to-brittle transition temperature may be lower than -20℃ since the results at -20℃ are close to the ones at room temperature. In order to improve the upper shelf energy it was recommended to:

• Reduce the carbon content. This reduces the volume of graphite in the structure. This also minimizes the risk of occurrence of chunk graphite and degenerated graphite found in the structure (Fig. 2).

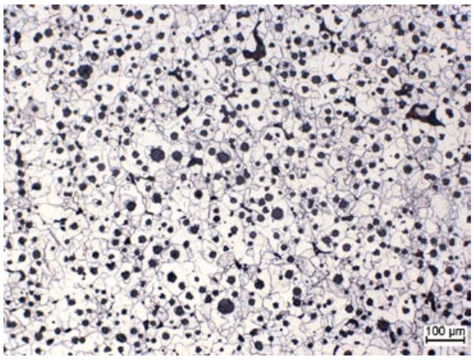

Fig. 1: Typical microstructure of impact sample (nital etched 4%)

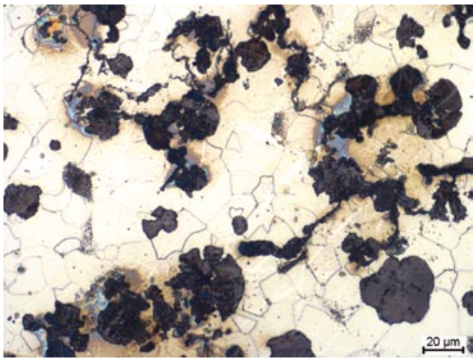

Fig. 2: Dross and irregular graphite particles – Case Analysis A (nital etched 4%)

Table 6: Image analysis results – Case Analysis A

Graphite	Pearlite	Nod/mm^2	Nodule
11%	5%	> 450	90%

Table 7: Chemical composition (wt.%) – Case Analysis A

C	S	Si	Mg	Ce	P	Cu
3.93	0.006	1.95	0.038	0.001	0.014	0.05
Mn	Ni	Cr	V	Ti	CE	
0.21	0.071	0.043	0.021	0.014	4.58	

CE = C + (Si + P)/3

Table 8: Charpy impact strength – Case Analysis A[9]

Sample	Impact strength (J)	
	RT	- 20°C
1	12.2	10.8
2	12.2	11.5
3	11.5	11.5
4	12.2	11.5
Average	12.0	11.3
Requirement		Ave.12, min. 9

• Reduce the nodule count to ~300 Nod/mm^2 since it is reported [6] that an excessively high nodule count decreases the upper shelf energy.

• Avoid dross formation by reducing the turbulence of the liquid metal flow during metal handling and mould filling.

(b) Case Analysis B

This second example also originated from a European foundry. The impact requirements were more difficult to reach comparatively to Case Analysis A since the test samples were drawn from the casting itself. The impact strength were measured on two trepans extracted from a wind generator hub casting (weight = 2 metric tons, wall thickness = 150 mm). The samples just met the impact test requirements at -20°C. The average test result was 11 J and the minimum specified for this section size thickness (60 < t < 200 mm, see Table 3) was 10 J. The nodule count varied from 30 to 100 Nod/mm^2 and the nodularity rating was lower than 80%. Table 9 presents the chemical composition whereas Fig. 3 illustrates the typical microstructure of the broken test bars.

Since the nodule count was extremely low in some locations, segregation of residual elements and microshrinkage occurred as illustrated by Fig. 4. The local composition of the segregation carbides showed Nb, V and Ti percentages higher than 10wt.% each despite those elements having bulk compositions lower than 0.01wt.%. In some areas, the estimated length of the carbide network was over 1 mm long. This constitutes a very severe defect in the casting which reduces significantly the impact strength and could initiate a fatigue failure. In order to secure the impact strength, it was suggested to:

• Reduce slightly the carbon content.

• Increase the nodule count by improving the inoculation efficiency. Melt conditioning or multi step inoculation could be implemented.

These two examples illustrated the effects of either high (450 Nod/mm^2) or low nodule counts (30–50 Nod/mm^2). Ductile irons having those nodule counts seem to have their impact strength negatively affected even if their chemical composition corresponds to usual recommendations for HSDIC.

Table 9: Chemical composition (wt.%) of the casting – Case Analysis B

C	S	Si	Mg	Ce	P	Cu	Mn	Ni	Cr	V	Ti	Nb	CE
3.62	0.003	2.00	0.034	0.001	0.013	0.024	0.12	0.026	0.028	0.008	0.008	0.002	4.29

CE = C + (Si + P)/3

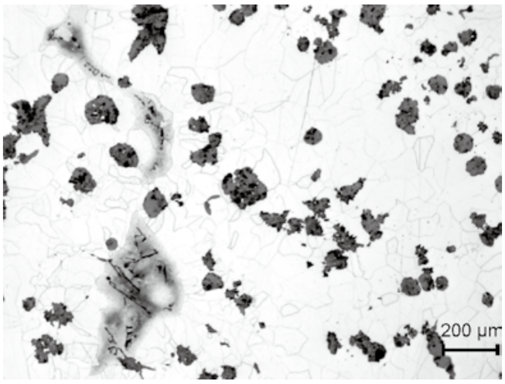

Fig. 3: Irregular graphite particles, segregation carbides and microshrinkage in a low nodule count area (nital etched 4%)

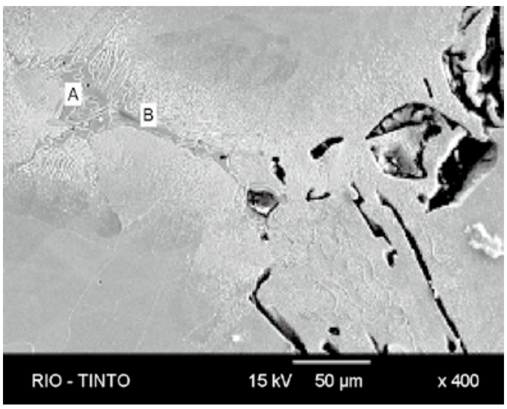

Fig. 4: Segregation carbides and microshrinkage in a low nodule count area (nital etched 4%)

2.2 Foundry experiment

The impact strength of HSDIC is very sensitive to dross or slag defect inclusions. Therefore a bottom filled mould including a sprue-filter-gate system limiting the liquid metal speed to ~0.5 m/s was designed. This criterion minimizes the oxidation of the liquid metal because the turbulence is reduced and allows the eventual inclusion to float on top of the mould cavity. A picture of the casting with its gating system is presented in Fig. 5. The experimental casting has the following dimensions 180 × 180 × 190 mm^3.

The silica sand moulds were resin bonded and the filter was a ceramic foam filter (10 ppi – 100 mm × 100 mm × 22 mm). The melting was performed with a 150 kg alumina crucible medium frequency induction furnace. The inoculation was performed in two steps. The first inoculant addition was made

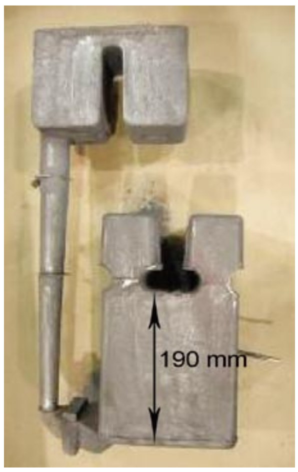

Fig. 5: Picture of the experimental casting

while the metal was transferred from the furnace to the ladle (~1/3 of the FeSi used in the charge). The second step was performed with a commercial FeSi block fixed in the pouring basin. Manual iron pouring was utilized. In order to optimize the pouring process, a graphite plug was used to prevent mould filling until the pouring basin was half full. Once a near steady state pour was attained, the plug was removed and mould filling commenced. The pouring temperature as measured in the ladle was in the range of 1,340–1,370℃.

The charge compositions of the three experimental heats are presented in Table 10. HS10 has a very clean charge and is not representative of industrial heats. However, this test will be used for the qualification of the effects of detrimental elements introduced via steel scrap or returns. HS13 and 14 included 27% steel scrap in their charge. The chemical compositions of the steel scrap and of the high purity pig iron are presented in Table 11.

Carbon and sulfur were analyzed by the combustion and inert gas fusion analysis (Leco) and the other elements by flame atomic absorption spectro-photometry except for P, Ce and Sb which were analysed by the inductively coupled plasma method. The FeSiMg and the FeSi75 alloy compositions are given in Table 12. The ferroalloys were analysed by X-ray fluorescence.

Table 10: Metallic charge composition (wt.%) of experimental heats

Material	HS10	HS13	HS14
High purity pig iron	67	67	67
Electrolytic iron (99.9%Fe)	27	0	0
Steel scrap	0	27	27
FeS	0.02	0	0
Fe_3P	153 g	153 g	153 g
FeSi75	1.1	1.1	1.3
Graphite	0.86	0.86	0.86
FeSiMg5	1.9	1.9	1.9
FeSi75 (ladle)	0.75	0.75	0.85
Sb (ladle)	15 g	15 g	15 g
Solid block inoculant (pouring basin)	0.08 kg	0.08 kg	0.08 kg

Table 11: Chemical composition (wt.%) of steel scrap and high purity pig iron (HPI)

Element	Steel	HPI
C	0.344	3.98
S	0.023	0.012
Si	0.05	0.06
P	0.009	0.004
Al	0.052	<0.001
Mn	0.37	0.008
Cu	0.043	0.023
Cr	0.041	0.028
Mo	0.007	<0.001
V	0.001	0.017
Nb	0.01	<0.001
Sn	0.005	0.001

Table 12: Chemical composition (wt.%) of the ferroalloys

Element	FeSi75	FeSiMg
Fe	24	46
Si	74.5	45
Ca	0.1	0.8
Al	0.6	0.9
Mg	-	4.8
Ce	-	0.44
La	-	0.23
Zr	0.03	-

2.3 Microstructures and image analysis

The sketch in Fig. 6 represents the central vertical plane of the casting; consequently position TM2 is the geometrical center of the casting. The microstructure of the casting was investigated at 6 positions (TM1 to TC3). Thermocouple measurements were taken at a 1 cm distance from the mould surface. In addition to the microstructures, the nodule counts, the nodularity and the pearlite percentage were quantified at position TM2. Note that the nodule count includes only the graphite particles that are considered nodular. This gives a lower nodule count than estimated visually by a chart comparison. A minimum of 25 fields was investigated in the routine.

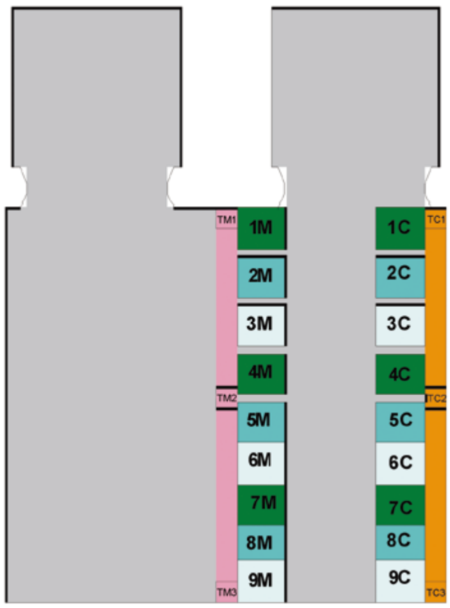

Fig. 6: Casting sketch with the location of the samples for microstructural examination (TM*x* and TC*x*) and for the impact tests samples (*x*M and *x*C)

2.4 Impact tests

Standard V-notch Charpy bars were machined and tested per ASTM standard A327-91. The tests were performed at room temperature, -20℃ and -40℃. The sample locations are also indicated in Fig. 6. The samples located in green squares (1M, 4M, 7M, 1C, 4C and 7C), were tested at room temperature. Samples 2M, 5M, 8M, 2C, 5C and 8 C were tested at -20℃. The remaining samples were tested at -40℃.

3 Results and discussion

3.1 Chemical composition

The chemical analyses of the castings at location TM2 are presented in Table 13. The analytical methods are the same as those detailed for the charge materials.

Table 13: Chemical composition (wt.%) of experimental heats

Element	HS10	HS13	HS14
C	3.36	3.15	3.2
S	0.010	0.007	0.008
Si	2.32	2.10	2.42
Mg	0.051	0.053	0.056
P*	0.017	0.023	0.023
Al	0.021	0.018	0.02
Cr	0.024	0.048	0.041
V	0.012	0.013	0.013
Ti	0.007	0.010	0.010
Mn	0.018	0.12	0.13
Ni	0.054	0.070	0.071
Cu	0.020	0.054	0.060
Ce*	0.008	0.007	0.008
Sb*	0.004	<0.004	<0.004
CE	4.13	3.85	4.01

* Inductively coupled plasma

The chemical composition of the casting produced in HS10 shows very low percentages of segregating (Cr, V, Ti, P, Mn) and pearlite promoting (Cu, Mn, Mo) elements as the charge material included 27% electrolytic iron. The objective of this test was to obtain a reference material to which subsequent heats, having higher residual element percentages, could be compared.

The charge composition of HS13 is similar to that of HS10 except that the electrolytic iron was replaced by steel scrap. Consequently, the residual and pearlite stabilizing element percentages increased. The lower carbon and silicon levels in HS13 are likely due to the increased level of oxides introduced in the charge containing steel scrap in place of the electrolytic iron. In HS14, FeSi75 percentages were adjusted in order to compensate for the oxidation loss experienced in HS13. The correction was slightly excessive and the final Si content was higher than in HS10.

3.2 Microstructures and image analysis

Figures 7, 8 and 9 present the typical microstructures of the sample located at TM2 for each experimental casting. The graphite particles are spherical and the matrix was free of inclusions such as dross or slag entrapment. The microstructures at positions TC2 were similar to those of TM2. The nodule density was not significantly different. Since TC3 (as shown in Fig.10) is located at the cube edge, the cooling rate during solidification is higher than for TMs samples. Thus a more significant difference can be observed in the microstructure.

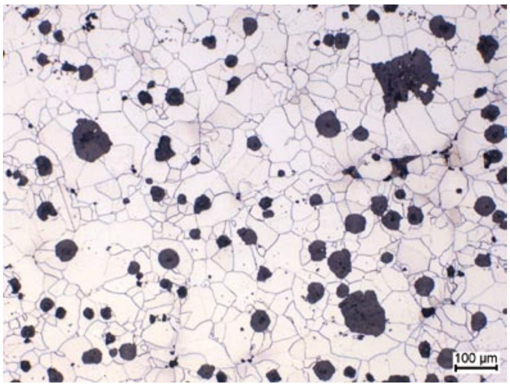

Fig. 7: Typical microstructure of heat HS10- Sample TM2 (nital etched)

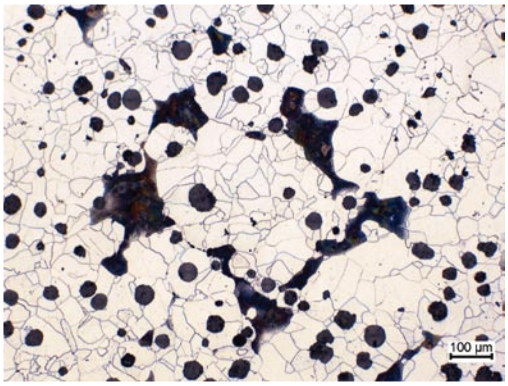

Fig. 8: Typical microstructure of heat HS13-Sample TM2 (nital etched)

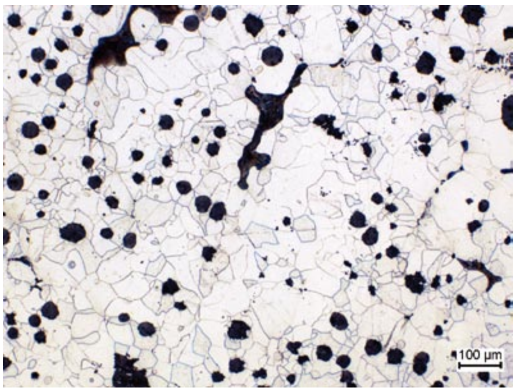

Fig. 9: Typical microstructure of heat HS14-Sample TM2 (nital etched)

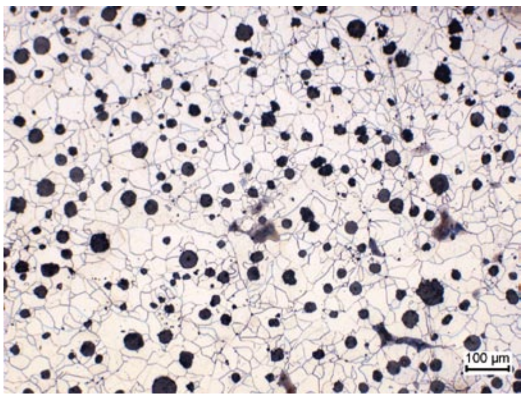

Fig. 10: Typical microstructure of heat HS13-Sample TC3 (nital etched)

The image analyses results are presented in Table 14. The microstructures of the experimental castings are comparable except for the pearlite percentages which are higher in Heats 13 and 14 when compared to HS10. This is caused by the higher percentage of pearlite forming elements that were introduced by the steel scrap as charge materials. In HS14, the pearlite percentage is slightly lower than in HS13. It is likely that the higher percentage of silicon comparatively to HS13 reduced the pearlite fraction.

Table 14: Image analysis results at location TM2

HS	Graphite (%)	Pearlite (%)	Nod/mm^2	Nodule (%)
10	10.5	<1%	95	93
13	10.6	8%	92	93
14	10.6	4%	106	92

3.3 Impact tests

Table 15 presents the impact strength of the samples drawn from the three experimental castings. The table also shows the average values at each position and each temperature. The position numbers refer to Fig. 6. In Fig. 11, the results are plotted against the testing temperature.

Table 15: Charpy impact strength (J)

		HS10		HS13		HS14	
T (°C)	Position	Middle	Side	Middle	Side	Middle	Side
23	1	18	18	16	18	15	15
23	4	16	18	16	16	16	16
23	7	16	19	16	18	16	18
	Ave.	16.7	18.3	16.0	17.3	15.7	16.3
-20	2	15	15	14	15	9	12
-20	5	15	16	14	11	12	14
-20	8	18	18	15	18	14	15
	Ave.	16.0	16.3	14.3	14.7	11.7	13.7
-40	3	11	8	9	9	7	7
-40	6	12	12	7	9	9	11
-40	9	14	14	15	15	11	11
	Ave.	12.3	11.3	10.3	11.0	9.0	9.7

The impact test results reflect the microstructures and the chemical compositions of the experimental heats. As expected, HS10 presents the highest impact strengths for all testing temperatures. Moreover, the as-cast impact strength at -40℃ is still higher than the impact requirement for grade EN-GJS-350-22U-LT for castings with relevant thickness of 60 < *t* < 200 mm. HS13 has a marginally higher impact strength compared to HS14. For instance at -20℃, HS13 still fulfills the EN-GJS-400-18-LT impact strength criterion (ave. 12 J, min. 10 J) which is not true for HS14.

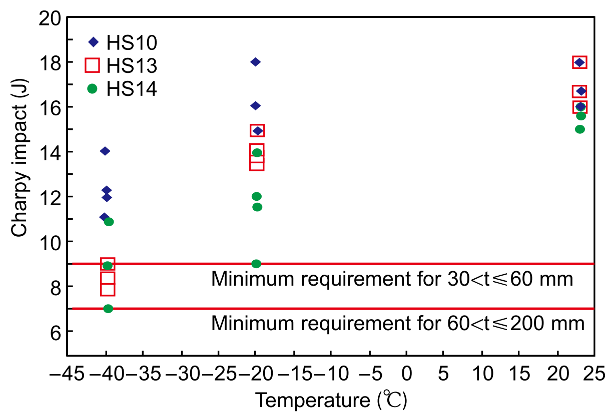

Fig. 11: Impact strength *vs* temperature at position TM2

4 Quality index empirical models

Many tools are available in order to determine the quality of a ductile iron casting. The chemical analysis is obviously one of the most precise methods. However, the relative effect of each element on a specific characteristic is not revealed by a simple chemical analysis. The strength to promote pearlite, to segregate or to degrade graphite is different for each element. Moreover, when they are combined, they often have interactions that can alleviate or accentuate their effects. Models developed by different authors [9-13] were used to compare the experimental HSDIC to the case analyses presented previously in this paper, but it is not the purpose of this paper to present the calculation models.

As a result, empirical models have been developed in order to calculate a single number that can be used to compare one ductile iron to another for a specific property.

Table 16 presents the chemical compositions that were used to calculate the quality indexes that are given in Table 17. The experimental heat with the highest properties (HS10) also exhibits the best Quality Index in five of the six models. However, the opposite is not totally verified. For instance, the lowest impact strengths at -20℃ were those of Case Analysis B, but the QI numbers calculated for this casting are not the worst: they are even better than those of HS13 and HS14. However, the nodule count and the nodularity were the

Table 16: Chemical composition (wt.%) used in the quality indexes calculation

Elements	S	Mn	Ti	Cr	V	Cu	P	Ni	Al	Mo	Co	Sn
HS 10	0.010	0.018	0.007	0.024	0.012	0.020	0.017	0.054	0.021	0.001	0.025	0.001
HS 13	0.007	0.012	0.010	0.048	0.013	0.054	0.023	0.067	0.018	0.003	0.026	0.003
HS 14	0.008	0.013	0.010	0.041	0.013	0.060	0.023	0.071	0.020	0.003	0.026	0.004
Case Analysis A	0.006	0.210	0.014	0.043	0.021	0.050	0.014	0.071	0.007	0.003	0.030	0.003
Case Analysis B	0.003	0.120	0.008	0.028	0.008	0.024	0.013	0.026	0.013	0.003	0.016	0.002

Table 17: Values of the different quality indexes (QI)

Reference	Pearlite promoter				Purity	Segregation
	Riposan (P_x=Pearlitic influence factor) [9]	French Automotive Casting, Inc. [10]	Decrop M, et al.[11]	Motz & Orths = % ferrite [12]	Thielemann = purity [13]	Riposan (FS = Segregation Factor)[9]
Better to	Minimize	Minimize	Minimize	Maximize	Minimize	Minimize
HS 10	**0.529**	**0.162**	**0.325**	**86**	0.067	**0.730**
HS 13	1.09	0.462	0.570	69	0.080	1.340
HS 14	1.609	0.481	0.561	67	*0.085*	1.278
Case Analysis A	*1.700*	*0.525*	*0.724*	*62*	0.080	*1.625*
Case Analysis B	0.995	0.300	0.363	76	**0.061**	0.953

Bold = Favourable: *Italic = Detrimental*

lowest and negatively affected the properties. This is a clear illustration that the microstructure has a major influence on the final properties of the HSDIC. A Quality Index that could take into account the microstructure in addition to chemical composition would probably be more representative of the mechanical properties of HSDIC.

5 Concluding remarks

The objective of this paper was to illustrate how the final microstructure is crucial for achieving high impact strength.

In order to produce high quality HSDIC, the first evident factor is the chemical composition. The typical composition ranges were illustrated in this paper and discussed in details elsewhere [6]. In addition to the general chemistry, defects such as chunk graphite and dross have to be avoided. These defects are also thoroughly discussed in other references[14].

Five examples of as-cast HSDIC were discussed including two experimental castings that have their impact strengths above the EN-GJS-350-22U-LT requirements (-40℃ : $60 < t \leqslant 200$ mm). A detailed characterisation of these DI was provided including the foundry process.

The second industrial example had a very good chemical composition and a favourable Quality Index. However it presented the lowest impact strength of the group of samples investigated. The final microstructure, which is reflective of the foundry process, is a key factor for achieving acceptable impact strength in addition to appropriate chemical composition.

In particular, nodule count, which has a major effect on pearlite content, microshrinkage, and the occurrence of segregation microcarbides, must be optimized. It is likely that a nodule count below 60 Nod/mm^2 is insufficient to avoid microshrinkage and/or microcarbides. It is, however, speculated that a maximum nodule count exists where the upper shelf energy is negatively affected. This maximum is not yet established since it may vary according to the chemical composition of the iron.

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