A STUDY ON THE TENSILE BEHAVIOUR OF SPHEROIDAL AND COMPACTED GRAPHITE CAST IRONS BASED ON MICROSTRUCTURAL ANALYSIS

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Abstract: *Spheroidal graphite cast iron (SGI) is mainly used in the transportation industry for applications such as engine blocks, turbo housings and exhaust manifolds because of its good castability, machinability, thermal exposure resistance, low cost, high Young's modulus and tensile strength. Nowadays, a new kind of cast iron known as Compacted Graphite Iron (CGI) or vermicular graphite iron, is replacing SGI because of its better thermal conductivity. This paper presents comparing analysis of SGI and CGI specimens tested under uniaxial tensile loading. Examinations were carried out on tensile specimens, in order to obtain results of Young's modulus, yield stress, ultimate tensile strength and elongation to failure. Referring to the fact that type, amount and distribution of microstructural constituents dictate the mechanical behaviour, tensile specimens cut from different cast plates were subjected to optical microscopy (OM) and scanning electron microscopy (SEM) analyses. Differences in microstructures were identified as causes of the different tensile properties.*

Key words: *Compacted graphite iron, spheroidal graphite cast iron, casting, yield stress, elongation to failure, Young's modulus, microstructure*

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1. Introduction

Although Compacted Graphite Iron (CGI) was first observed in 1940s, an unstable foundry production precluded its use for high volume production until advanced process control technologies became available [1-3]. Nowadays CGI is used for complex shape applications such as cylinder heads and engine blocks. As the demand for higher torque, lower weight and, consequently, lower emissions continues to grow, engine designers are forced to seek stronger materials with higher heat transfer efficiency. This is particularly true in the diesel sector where resolution of the conflicting performance objectives requires increased cylinder bore pressures. At these operating levels, the strength, stiffness and fatigue properties of traditional cast iron or aluminium alloys may not be sufficient to satisfy the design requirements maintaining low production costs. Referring to this, more detailed studies on mechanical and physical properties of CGI as a function of the content and morphology of its microstructural constituents were been carried out [4]. Due to its properties, several automotive manufactures have therefore evaluated CGI for their petrol and diesel cylinder head applications [5-7].
Despite that, the mechanical behaviour of CGI is not yet as well-known as those of spheroidal grey iron (SGI) and that fact leaves empty space for further CGI studies.
Taking into consideration the major differences between SGI and CGI, it must be considered their different amount and morphology of their microstructural constituents. SGI, with its graphite nodules, is so characterised by good castability, machinability, low cost, high Young's modulus and tensile strength [8,9]. Otherwise CGI, with its graphite worms, is well known for its lower weight and better thermal conductivity [10,11]. This study is focused on the understanding of how graphite morphology and matrix constituents dictate the differences in mechanical behaviour of these two classes of cast iron. In particular, tensile test, optical and electron microscopy analyses were carried out and the results are here reported.

2. Objectives

The aim of this study was first to evaluate and describe different mechanical behaviours of CGI and SGI specimens under given load conditions. Secondly, the repeatability of the melting process that involves about 30% of ferrous scrap and a cupola furnace was checked. Finally optical and scanning electron microscopy analyses were carried out to explain the different mechanical behaviours of the two materials.

3. Material and Methods

In this study, 12 tensile specimens were tested. The specimens were extracted from CGI and SGI green sand cast plates taken from two different production batches to check the process repeatability.
Table 1 and table 2 report chemical compositions of the melts the plates were cast from. Before the pouring, the melt (with a sulphur content lower than *0.01%* wt.) was inoculated by adding ferrosilicon alloys and modified with Fe-Si-Mg master alloys. In the production of CGI castings also Ti was added. In all cases, the pouring temperature was 1400°C.
Tensile tests were carried out on the uniaxial loading tensile testing machine INSTRON® 1343, according to the UNI EN 10002-1 standard. Figure 1 reports the geometry of specimens machined according to the UNI EN 1563 standard. As shown in the figure tensile test were carried out on 14 mm diameter and 90 mm gauge length

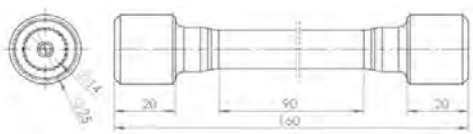

Fig. 1. *Geometry of tensile specimens*

specimens. Brinell hardness test were also carried out according to UNI EN 10003-1 standard. After tensile and hardness tests, a *ZEISS Evo50®* SEM was used to analyse the fracture surfaces. Both secondary and backscattered electron analyses were carried out. Energy-dispersive X-ray spectroscopy (EDS) technique was also used to evaluate the presence of carbides. Finally, metallographic samples were extracted near the fracture surfaces to evaluate the graphite morphology and the percentage fraction of ferrite and perlite. The specimens were prepared using standard metallographic techniques, including mechanical grinding, polishing and etching. Qualitative and quantitative metallographic analyses were carried out using a *ZEISS Axio®* optical microscope (OM) and *Image Pro®* digital image analysis software. Nodularity and vermicularity of the two cast irons were evaluated according to ISO 16112 and ISO 945 standards.

First batch specimens chemical composition Table 1

Elements	C	Si	Mn	P	S	Ni	Cr	Cu	Mg	Sn	Ti	Al
SGI	3,66	2,6	0,218	0,032	0,004	0,069	0,062	0,052	0,055	0,013	0,034	0,011
CGI	3,68	2,67	0,215	0,029	0,007	0,068	0,061	0,05	0,014	0,013	0,073	0,01

Second batch specimens chemical composition Table 2

Elements	C	Si	Mn	P	S	Ni	Cr	Cu	Mg	Sn	Ti	Al
SGI	3,63	2,65	0,276	0,036	0,002	0,06	0,083	0,077	0,049	0,011	0,033	0,011
CGI	3,63	2,57	0,272	0,034	0,005	0,06	0,082	0,075	0,012	0,011	0,074	0,011

4. Results and Discussions

Figure 2 reports engineering (a) and real (b) stress-strain curves of SGI and CGI tensile specimens from both the two production batches. It is clear how, according to the results of tensile tests, SGI specimens were much more ductile then CGI ones. This difference in elongation to failure can be explained by observing the fracture surfaces of the two classes of cast iron (fig. 3). It is clear that cleavage is the dominant fracture mechanism for both the materials. However, for CGI specimens, cleavage planes are wider and the very high decohesion at the matrix-graphite interface can be seen as cause of their lower ductility and different behaviour in the plastic field. Furthermore SGI ultimate tensile strength and yield strength were significantly higher than CGI ones. An explanation of this behaviour can be found in the different hardness values of the two materials (tab. 3). As clearly shown (fig. 4 and tab. 4) this difference may be in turn due to the different perlitic fractions of the matrices of the two materials. This is the reason for the higher hardness, yield strength and ultimate tensile strength values of SGI specimens. By considering the differences between the mechanical behaviour of the four batches (fig. 2 and tab. 3), it is clear how, while CGI batches seems to have a very similar behaviour, SGI ones showed about a 5 % difference in UTS and YS values and 25% difference in E%. The explanation of such a different behaviour can be found in the microstructural differences observed in the specimens of the two batches (tab. 4). Besides the sam e nodularity (due to the similar Mg content of the melts), batch 1 specimens were first characterised by a lower graphite content with a little bit higher nodule density and a v ery lower average nodule area. Further more, it is clear that batch 1 SGI seems to have higher (lower) content of perlite (ferrite) respect to SGI batch 2. This difference is in tur n due to small differences in chemical compositions of the two batches and is also responsible for their difference in hardness.

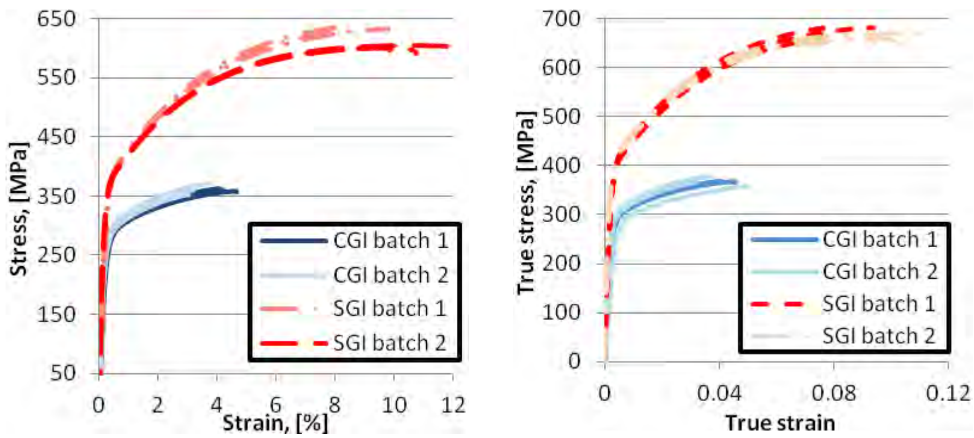

Fig. 2. *Engineering (a) and real (b) stress-strain curves for specimens extracted from plates coming from two different production batches of SGI and CGI.*

Average (st. deviation) of tensile and hardness tests data for SGI and CGI samples Table 3

Series:	**UTS,[MPa]**	**YS,[MPa]**	**E[%]**	**E,[GPa]**	**BHN**
SGI_Batch 1	632 (3)	377 (4)	8.4 (0.9)	170 (15)	206 (1)
SGI_Batch 2	602 (2)	360 (7)	10.9 (1.1)	165 (11)	182 (2)
CGI_Batch 1	361 (1)	282 (3)	4 (0.3)	127 (9)	155 (1)
CGI_Batch 2	361 (9)	278 (8)	3.3 (0.4)	123 (3)	151 (2)

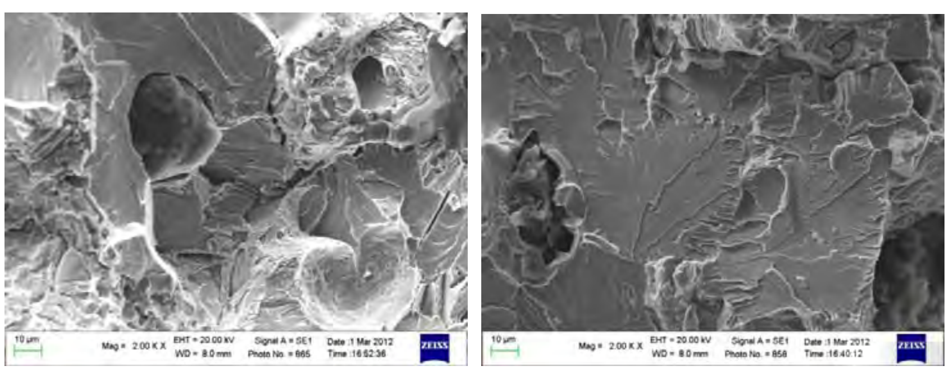

Fig. 3. *High magnification SEM micrographs on the fracture surfaces of SGI (a) and CGI (b) tensile specimens. Cleavage fracture mechanism is evident in both the cast irons.*

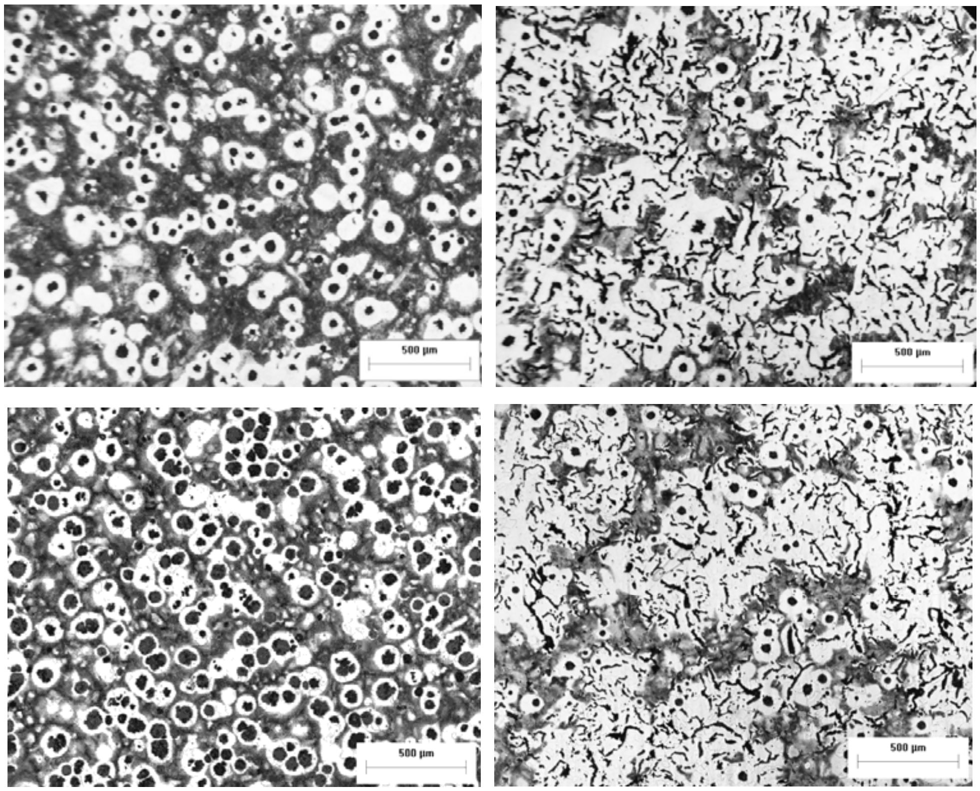

Fig. 4. *OM micrographs after Nital etching of: 1st batch SGI specimen (a); 1st batch CGI specimen (b); 2nd batch SGI specimen (c); 2nd batch CGI specimen (d). Graphite nodules and worms (black), ferrite islands (white) and perlite (grey) are evident.*

Average values (and standard deviations) of microstructural parameters evaluated on SGI and CGI tensile specimens. Table 4

Series:	Graphite %	Ferrite %	Perlite %	Nodule Area [mm^2]	Nodule Density [$1/mm^2$]	Nodularity % - Vermicolarity %
SGI_Batch 1	6 (1)	32 (2)	64 (1)	765 (142)	74 (6)	85 (3) – 12 (2)
SGI_Batch 2	12 (1)	45 (2)	43 (3)	1850 (194)	66 (2)	82 (3) – 13 (1)
CGI_Batch 1	11 (1)	59 (1)	30 (1)	882 (55)	125 (7)	10 (4) - 83 (1)
CGI_Batch 2	14 (0)	56 (1)	30 (1)	890 (4)	158 (7)	11 (2) - 83 (4)

5. Conclusions

In this paper CGI and SGI specimens from two different manufacture batches were tested, Specimens were subjected to mechanical tests, optical and electron microscopy analyses and the results can be summarised as follows:

• UTS, E% and Young's modulus were higher for SGI specimens than for CGI ones. Different graphite morphology in the two materials is the cause for such behaviour.
• Cleavage was the dominant fracture mechanism for both the materials but CGI specimens showed higher decohesion at

the matrix-graphite interface resulting in lower ductility.

• YS and H BN were also higher for the SGI specimens. This is a conseq uence of the higher perlite content of this cats iron.

•. Different mechanical behaviours for two nominally identical production batches were noticed.

• Mechanical properties can wid ely range due to little diff erences in chemical compositions of the melts that has thus to be highly controlled during the process.

Acknowledgements

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