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Pearlitic Ductile Cast Iron: mechanical properties gradient analysis in graphite elements

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Abstract

Ductile Cast Irons (DCIs) are able to combine a good versatility and high performances with a low cost, especially if compared to steels with analogous performances. For these reasons, although these grades have been relatively recently developed, DCIs applications are more frequent. Analyzing the damaging micromechanisms in static, quasi-static or cyclic conditions, the analysis of the role played by the graphite elements is not univocal. Sometimes, they are considered as voids embedded in a more or less ductile matrix, sometimes they are considered as a soft but homogeneous material. In this work, the role played by the graphite nodules in pearlitic grains is reviewed and their mechanical properties are investigated by means of nanohardness tests.

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Keywords: Ductile cast irons; Graphite elmements; Damaging micromechanisms; Nanoindentation tests.

1. Introduction

Relatively recently developed and optimized (Labrecque and Gagne, (1998) and Rundman and Iacoviello (2016)), Ductile Cast Irons (DCIs) offer an interesting combination of good mechanical properties (similar to or even better than carbon steels) and good castability (peculiar of cast irons) controlling the graphite nodules shape (nodular and not lamellar) by means of nodularizing elements like Mg and not by means of long heat treatments (as in malleable cast irons) with a consequent strong reduction of costs.

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Considering the role played by the graphite nodules in the damaging micromechanisms during static, quasi static or cyclic loading, some authors focused their attention on the debonding matrix – graphite elements and, as a consequence, they propose some analytic laws able to describe single or multiple voids growth, only dependent on the voids geometries and on the matrix behavior (a review of these models is available in Hutter et al. (2015)). Recent experimental analysis showed a more complex role played by the graphite elements, depending on the loading conditions, the graphite nodules morphology and the matrix microstructure. Considering tensile loading conditions (Di Cocco et al. (2014)) the role played by the graphite nodules on the damaging micromechanisms can be summarized as follows:

- Graphite nodules – matrix debonding (Fig. 1): this mechanism is more often observed in pearlitic DCIs. Although it is often considered as the unique mechanism in ferritic DCI, and the only mechanism considered in the simulations based on voids ductile growth, according to Di Cocco et al. (2014b) it is the less important in these grades;
- Graphite nodules “internal debonding (or “onion-like” mechanisms, Fig. 2): cracks initiate and propagate inside the graphite nodule, with an external graphite shell and an internal nucleus that become more and more evident with the increase of the macroscopic deformation;
- Crack initiation in the nodule core (Fig. 3): cracks initiate corresponding to the nodule center, probably corresponding to a solidification site (e.g., non metallic inclusion) and propagate with a progressive disaggregation of the graphite nodule.

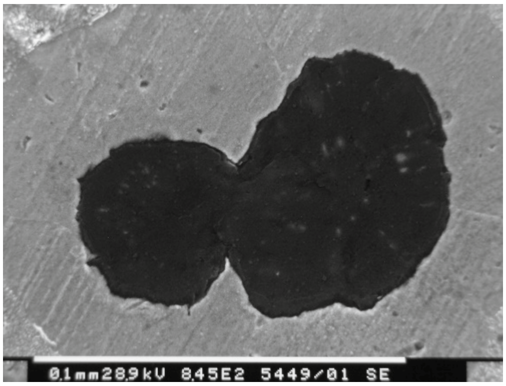

Fig. 1. Ferritic-pearlitic DCI: graphite-nodule debonding, Di Cocco et al. (2014b).

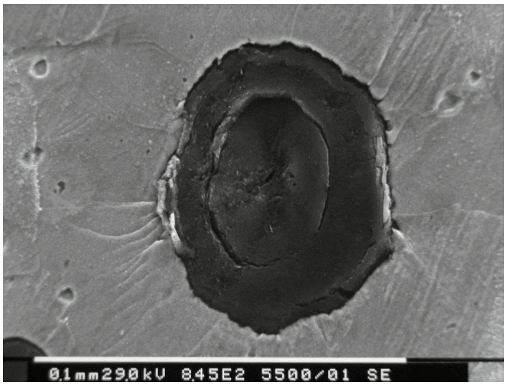

Fig. 2. Ferritic-pearlitic DCI: “onion-like” mechanism with ferrite-graphite debonding and slip bands in the ferritic shell, Di Cocco et al. (2014b).

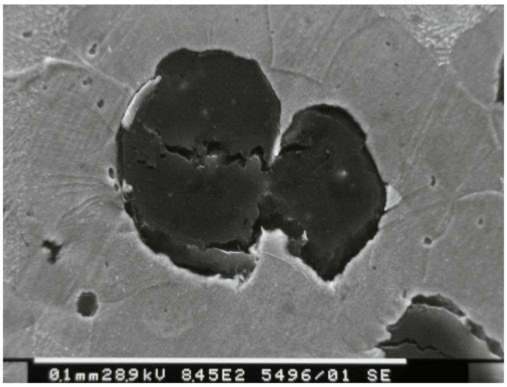

Fig. 3. Ferritic-pearlitic DCI: internal crack propagation and opening (“disaggregation” mechanism) with slip bands in the ferritic shell, Di Cocco et al. (2014b).

The activation of the "onion-like" mechanism could be justified with the presence of a mechanical properties gradient inside the graphite nodules. In a preliminary work, Iacoviello et al. (2013) performed some nanoindentation and some non standard wear resistance tests showing that graphite nodules were characterized by an internal mechanical properties gradient, with the core (obtained directly from the melt) that was characterized by lower nano hardness values and wearing resistance and the outer shell (obtained according to carbon solid diffusion mechanism) that is characterized by higher nano hardness values and wearing resistance. This work (Iacoviello et al. (2013)) was based only on preliminary results obtained on a fully ferritic DCI.

In this work, a fully pearlitic DCI has been investigated more systematically performing a quick mapping of 144 (12x12) nanoindentation tests on each investigated nodule.

2. Investigated alloy and experimental procedure

A pearlitic DCI (EN GJS700-2) characterized by a good nodularity has been investigated (chemical composition and mechanical properties are shown in Tab.1 and Tab.2, respectively)

Table 1. EN GJS700-2 chemical composition.

C	Si	Mn	S	P	Cu	Mo	Ni	Cr	Mg	Sn
3.59	2.65	0.19	0.012	0.028	0.04	0.004	0.029	0.061	0.060	0.098

Table 2. EN GJS700-2 mechanical properties.

E [GPa]	R_m [MPa]	R_{p02} [MPa]	A% min
180	700	400	2

DCI specimens has been metallographically prepared and nanoindentation tests have been performed according to a 12x12 grid. The choice of the nodules to be investigated on the metallographically prepared surface is a crucial point in the procedure: it is necessary to choose larger nodules in order to have more possibilities to "cut" the nodule corresponding to the maximum diameter. In Fig. 4, the different possibilities offered by the intersection of a plane with a nodule constituted by an outer shell and by a core. A small "black spot" on the metallography can be connected to a situation Fig. 4a, with no intersection with the core (if present!). Instead, larger "black spot" on the metallography are probably connected to large nodule cut near or corresponding to the maximum diameter. In this case, if a core exists, it can be observed on the metallography and can be analysed by means of the nanoindentation test procedure described below.

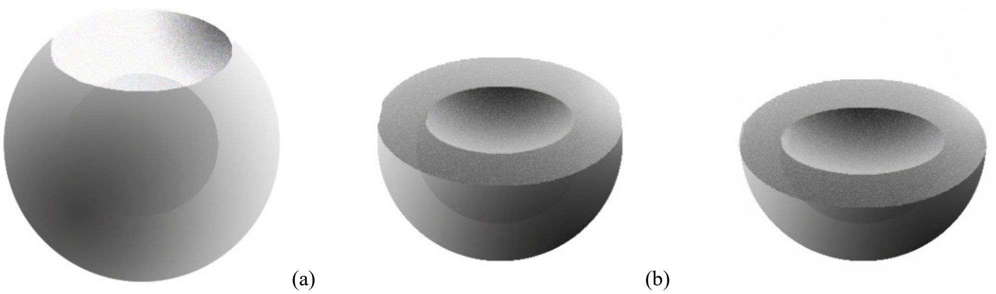
(a) (b) (c)

Fig. 4. Nodule cut by a plane: a) no intersection with the core; b) intersection with the core (general cut); c) intersection with the core corresponding to the maximum diameter.

Quick Nanoindentation mapping have been performed by means of a Anton Paar Nanoindentation Tester (NHT[3], Fig. 5), with the following test parameters:

- Indenter type: Berkovich
- Loading type: linear
- Loading rate: 120 mN/min
- Maximum load: 2 mN
- Unloading rate: 120 mN/min

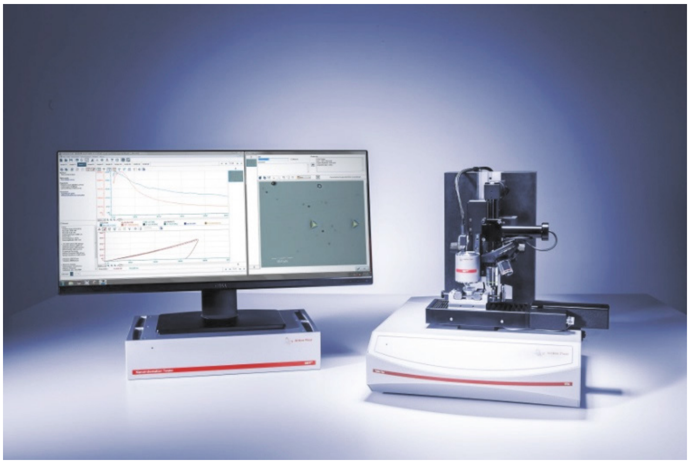

Fig. 5. Anton Paar Nanoindentation Tester (NHT[3]).

All the results were obtained using the Oliver - Pharr method (under the hypothesis of a sample Poisson's ratio of 0.3, for the elastic calculations), Oliver (1992).

It is worth to note that the mechanical properties are calculated on the assumption of a flat testing surface. If the indenter comes in to contact with a surface peak, the non-uniform contact increases the localized stress corresponding to the contact point, with a greater penetration depth and, consequently, a lower calculated hardness.

In order to define the optimum testing conditions, according to International Standard ISO 14577-4, R_a value should be less than 5% of the maximum penetration depth. Anyway, nanoindentation tests average values are similar on smooth or rough samples, but standard deviation value is larger in the second case, Iacoviello et al. (2013).

We decide to use the "Quick matrix" in order to characterize the 144 Nanoindentation in less than 30 minutes. The distance between each indentation is 5 microns, (Fig 6).

The quick mapping is a two-dimensional tool for mapping the mechanical properties of complex surfaces, Randall (2009), this allow us to generate a modulus and hardness mapping over the all nodule (Fig. 7 and 8) for a better understanding of the gradient of mechanical properties.

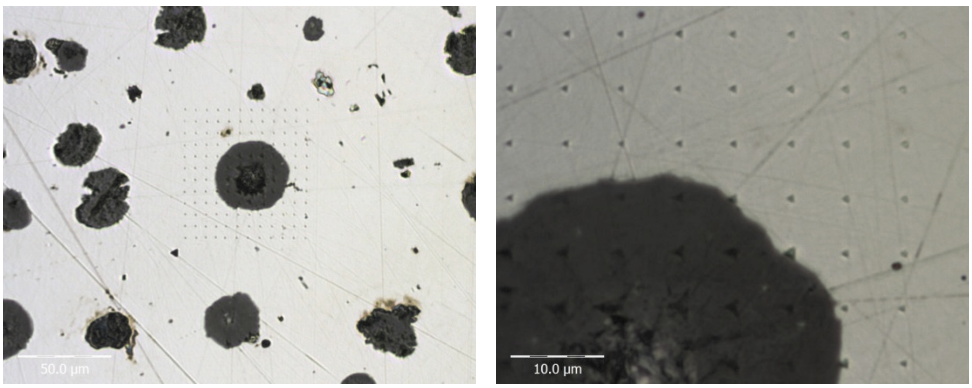

Fig. 6. Optical micrograph of the Quick mapping.

3. Results and discussion

Although the surface corresponding to the graphite nodules is not perfectly plane (due to the differences in the wearing resistance, Iacoviello et al. (2013)) the results obtained for the investigated DCI are really interesting. A pearlitic DCI (EN GJS700-2) characterized by a good nodularity has been investigated (chemical composition and mechanical properties are shown in Tab.1 and Tab.2, respectively). In Fig. 6 and 7, the results obtained with two nodules are shown, focusing the Eit, formally called the "indentation modulus" (Fig. 7a and 8a, respectively), and Hit, the indentation hardness (Fig. 7b and 78b, respectively). Focusing on the Eit results, differences between hypothetical nodule "core" and nodule "shell" are not evident. The mean value (about 20 GPa) is obtained in all the investigated nodules, to be compared with a Eit mean value of about 190 GPa obtained in the matrix. Considering the Hit, the results are different. If the investigated nodule is cut according to situations described in Fig. 4b or 4c, in the center of the nodule is observed a large spot with a lower Hit value. The "nodule core" diameter are different between the two nodules in Fig. 7 and 8 due to the different nodule cutting conditions (Nodule 1 in Fig. 7 is probably near to the condition described in Fig.4b; instead, Nodule 2 in Fig. 8 is near to the condition described in Fig. 4c). Considering a Fe-C diagram with a Si content close to 2.65 (Fig. 7), assuming a really low cooling rate value, graphite volume fractions obtained directly during the solidification stages (equilibrium Liquid-Grafite, M, and eutectic solidification, E) and during the cooling stage due to carbon atoms solid diffusion (A), have been evaluated considering a concentric homogenous spherical model. The corresponding graphite nodulus diameters are:

$$D_{C_M} = 0.38 D_{\text{nodule}}$$
$$D_{C_M + C_E} = 0.89 D_{\text{nodule}}$$
$$D_{C_M + C_E + C_A} = 0.95 D_{\text{nodule}}$$

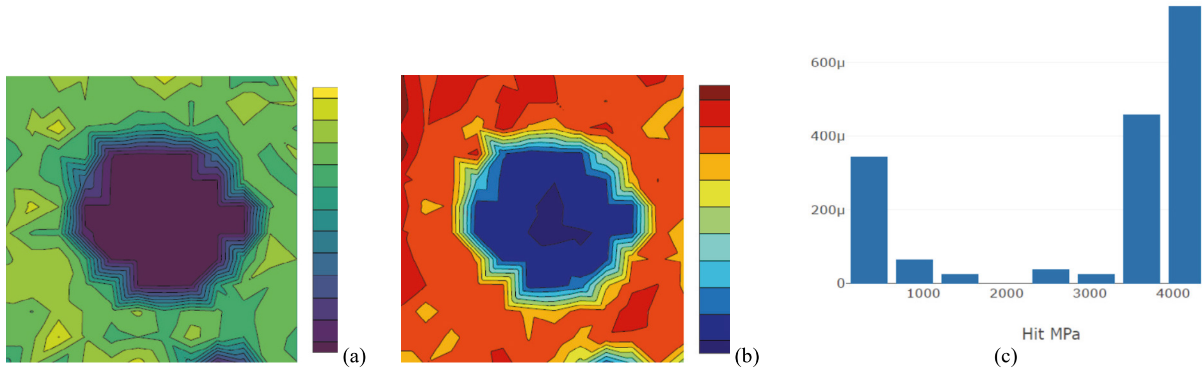

Fig. 7. Eit (a) and Hit (b, c) evolution in and around a nodule (nodule 1).

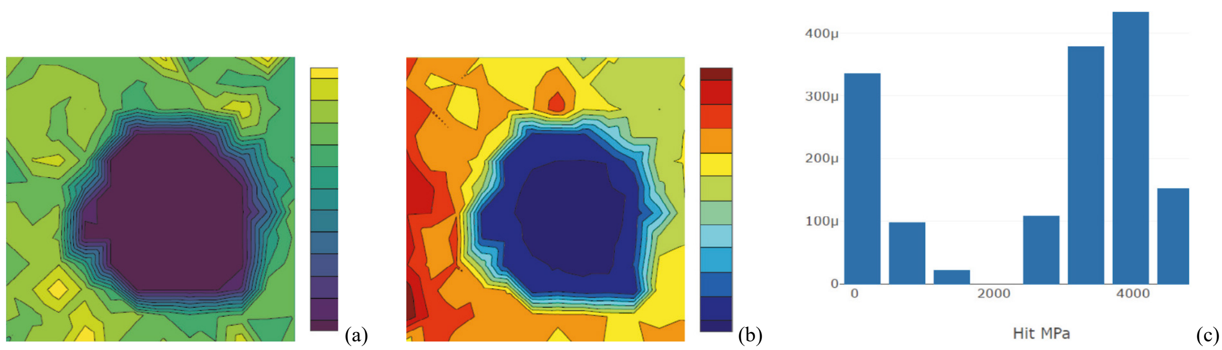

Fig. 8. Eit (a) and Hit (b, c) evolution in and around a nodule (nodule 2).

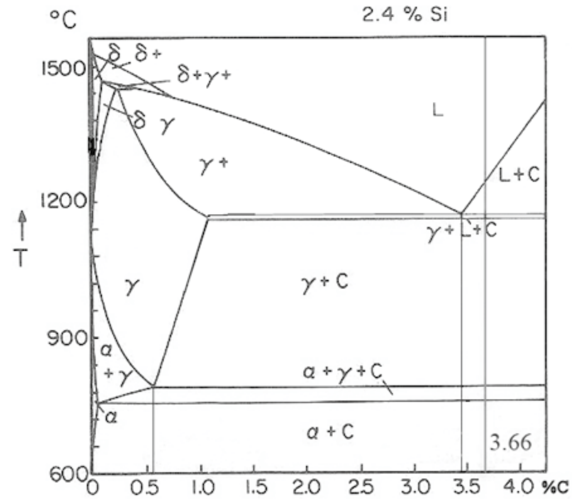

Fig. 9. Fe–C diagram for % Si = 2.4 according to Minkof (1983).

These values, calculated under the hypotheses described above, correspond with the results obtained in Fig. 6b, where probably the nodule has been cut corresponding or near to the maximum diameter. Three different zones are evident: a nodule core (due to the direct solidification from the melt, with the lowest Hit values), a first nodule shell (due to the eutectic solidification, with intermediate Hit values) and a second outer shell (due to the carbon atoms solid diffusion, with the highest Hit values measured in the graphite nodules). Comparing these result with the damaging micromechanisms described in Fig. 1-3, it is possible to summarize that the presence of a mechanical properties gradient inside the graphite nodules can be ascribed to the different graphite nodules growth mechanisms (direct solidification from the melt, eutectic solidification, carbon atoms solid diffusion). The internal cracks nucleate corresponding to the graphite nodules nucleations sites (e.g., microvoids). Instead, the so called “onion-like” mechanism mainly initiate and propagate corresponding to the interface between the nodule core (obtained directly from the melt) and the first shell, obtained during the eutectic solidification. In this stage, the increase of the graphite nodule is obtained via carbon atoms solid diffusion through an austenite shell. The evolution of the eutectic solidification, implies an increase of the austenitic shell thickness, with carbon atoms diffusion that become more and more difficult (Nakae et al. (2007)) up to the complete alloy solidification. As a consequence of the different graphite nodules growing mechanisms, different nanohardness values are obtained with a consequent possibility to activate different damaging micromechanisms during a tensile loading.

4. Conclusion

Considering the different damaging micromechanisms observed in DCIs, in this work the local mechanical properties in graphite nodules were investigated by means of nanohardness tests. On the basis of the experimental results, and of some simplified considerations on the nucleation and growth of the graphite nodules during a DCI solidification process, it is possible to summarize that:

- Graphite nodules are characterized by an internal gradient of mechanical properties (nanohardness);
- Nanohardness tests results allowed to identify three zones that correspond to the graphite core obtained directly from the melt, to the first graphite shell obtained during the eutectic solidification (via carbon atoms solid diffusion through an austenitic shell) and to a second graphite shell obtained during the cooling stage (due to the decrease of the carbon atoms solubility in the austenitic grains with the temperature decrease);
- Graphite nodules – matrix debonding is only one among the possible damaging micromechanisms in DCIs: the “onion-like” mechanism and the cracks initiation and propagation in the nodules center and propagation are other two possible damaging micromechanisms.

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