Focussed on: Fracture and Structural Integrity related Issues

Damaging micromechanisms characterization in a ferritic-pearlitic ductile cast iron

Vittorio Di Cocco, Francesco Iacoviello, Alessandra Rossi
Università di Cassino e del Lazio Meridionale, DICeM, via G. Di Biasio 43, 03043, Cassino (FR), Italy
v.dicocco@unicas.it, iacoviello@unicas.it, alessandra.rossi@unicas.it

Mauro Cavallini
Università di Roma "La Sapienza", DICMA, via Eudossiana 18, Roma, Italy
mauro.cavallini@uniroma1.it

ABSTRACT. The analysis of the damaging micromechanisms in Ductile Cast Irons is often focused on ferritic matrix. Up to ten years ago, for this grades of DCIs, the main damaging micromechanism was identified with the graphite elements – ferritic matrix debonding. More recent experimental results showed the presence of an internal gradient of mechanical properties in the graphite elements and the importance of other damaging micromechanisms, with a negligible importance of the graphite elements – ferritic matrix debonding mechanism.
In this work, damaging micromechanisms development in a ferritic – pearlitic DCI have been investigated by means of tensile tests performed on mini-tensile specimens and observing the specimens lateral surfaces by means of a scanning electro microscope (SEM) during the tests ("in-situ" tests). Experimental results have been compared with the damaging micromechanisms observed in fully ferritic and fully pearlitic DCIs.

KEYWORDS. Ductile Cast Irons (DCIs); Damaging micromechanisms; Microstructure influence.

INTRODUCTION

Ductile cast irons (DCIs) are characterized by a good castability and good mechanical properties (tensile strength, toughness, wear resistance): this peculiar behaviour is obtained only by means of the chemical composition control [1] (using Mg, Ca, or Ce) and not by means of long and expensive heat treatments (as in malleable irons). DCIs are characterized by a wide range of mechanical properties, mainly depending on microstructural factors, as present phases (characterized by volume fractions, grain size and phases distribution), graphite particles (characterized by number, size and shape) and defects (as porosity, inclusions, segregated elements etc.). Chemical compositions and many different heat treatments have been optimized in order to obtain different metal matrix microstructure, obtaining different combination of mechanical properties as yield strength, ductility, toughness, wear and fatigue resistance. Nowadays, ferritic, perlitic, ferritic-perlitic, martensitic, austenitic, bainitic and austempered ductile irons offer a wide range of mechanical properties at a lower cost than the older malleable iron.
In the last decades, the development of the damaging micromechanisms in DCIs have been investigated considering different loading conditions (e.g. tensile or fatigue loading conditions) and different matrix microstructures [2-9]. Main

damaging micromechanism of ferritic DCIs (maybe, the most investigated grades) was usually identified with the ferritic matrix - graphite nodules debonding [2]: microcracks in graphite nodules were also observed, but their influence was considered as practically negligible and ferritic DCIs were considered as a ductile porous material [10]. Recent experimental results [9, 11-13] demonstrated that the role played by graphite nodules in the ferritic DCIs damaging micromechanisms is more complex and can be summarized as follows:

- Graphite nodules are characterized by an internal mechanical properties gradient, with the core (obtained directly from the melt) that is characterized by lower nano hardness values and lower wearing resistance and the outer shield (due to the carbon solid diffusion mechanism) that is characterized by higher nano hardness values and wearing resistance;
- Considering tensile tests, in the elastic stage neither cracks nor microvoids initiations are observed both in ferritic matrix and in graphite nodules;
- "Pure" graphite nodule – ferritic matrix debonding is only seldom observed;
- It is often observed the initiation and growth of multiple cracks in the graphite nodules, between a "nodule core", roughly corresponding to the graphite obtained directly from the melt, and a "nodule shield", roughly corresponding to the shield due to the carbon solid diffusion mechanisms during the DCI cooling from the melt ("onion-like" damaging micromechanism).
- A second damaging micromechanism is often observed. It implies the initiation and growth of cracks corresponding to the nodule center, with a consequent disaggregation of the nodule.

The aim of this work is the analysis of the damaging micromechanisms in a ferritic-pearlitic DCIs, mainly focusing the graphite nodules role, by means of the Scanning Electron Microscope (SEM) observations of the lateral surfaces of mini-specimen during the execution of tensile tests ("in-situ" tests).

INVESTIGATED MATERIAL AND EXPERIMENTAL PROCEDURE

A fully ferritic-pearlitic EN GJS500-7 DCI (50% ferrite – 50% pearlite) was investigated (Tab. 1). Graphite elements in the investigated pearlitic DCI were characterized by a very high nodularity, higher than 85%, with a volume fraction of about 9-10%. Matrix microstructure is characterized by a ferritic shield around the graphite nodules, embedded in a pearlitic matrix.

C	Si	Mn	S	P	Cr	Mg	Sn
3.65	2.72	0.18	0.010	0.030	0.005	0.060	0.098

Table 1: Ductile cast iron EN GJS500-7 chemical composition (50% ferrite – 50% pearlite).

In order to perform the tensile tests, microtensile specimens were considered, with a length x width x thickness equal to 26 x 2 x 1 mm, respectively (Fig. 1).

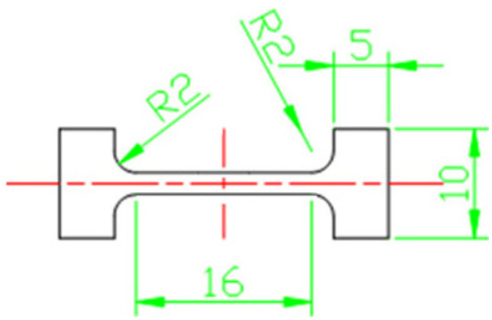


Figure 1: Mini-tensile specimen.

Specimens were ground and polished and etched (Nital 2) and pulled intermittently with a tensile holder and observed in situ using a SEM (step by step procedure), considering at least 20 graphite elements. During tensile tests, specimen deformation and applied load were measured by means of a Linear Variable Differential Transformer (LVDT) and two miniature load cell (10 kN each), respectively. Figs. 2a and 2b show the tensile holder with the mini-tensile specimen and the tensile test machine, respectively [9].

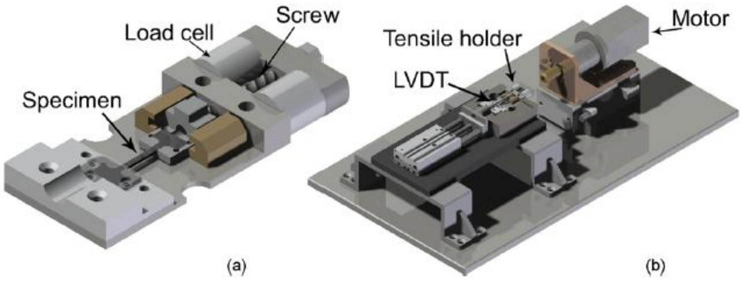


Figure 2: (a) Tensile holder with mini-tensile specimen; (b) tensile test machine.

EXPERIMENTAL RESULTS AND COMMENTS

The end of the elastic stage is characterized by the initiation of very short cracks inside the graphite nodules or corresponding to the ferritic shield – graphite nodules interface (Fig. 3). The increase of the macroscopic deformation implies the activation of different damaging micromechanisms with cracks that initiate and propagate in the graphite nodules (Fig. 4a), with the debonding at the interface ferritic shield – graphite nodules that is more and more evident (Fig. 4a and b) and with the presence of slip bands in the ferritic shield that, preferably, emanates corresponding to the graphite nodules equators (Fig. 5; different magnifications).

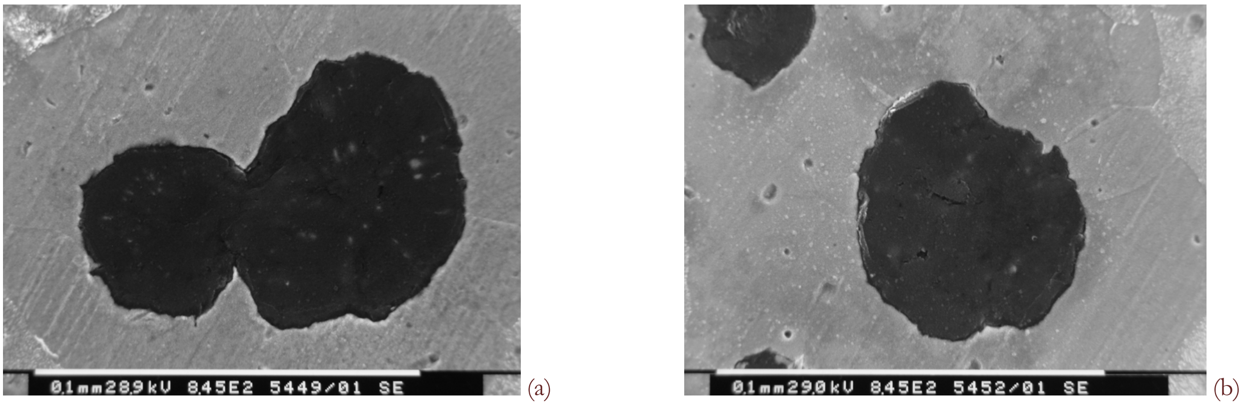


Figure 3: Damaging micromechanisms corresponding to the end of the elastic stage. Debonding between ferritic matrix and graphite nodule (a, b); Crack initiation in the graphite nodule (b).

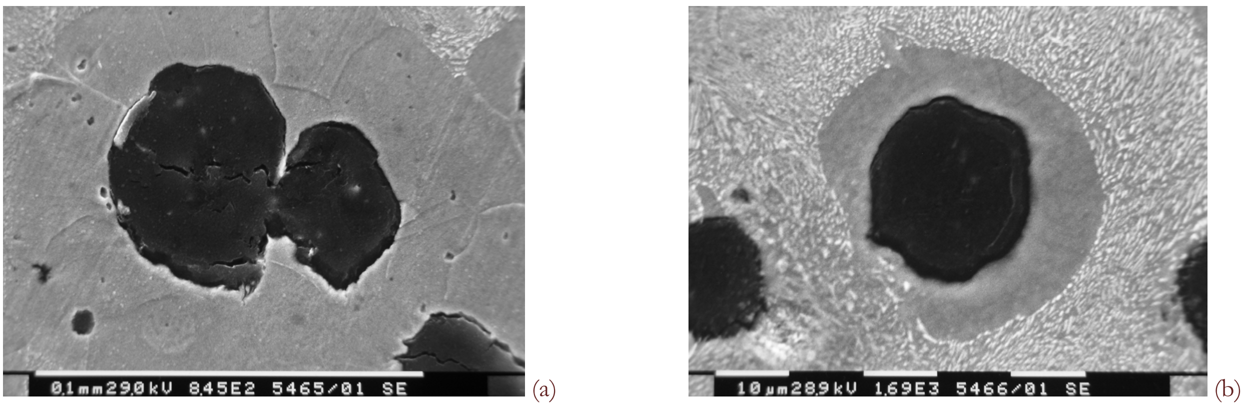
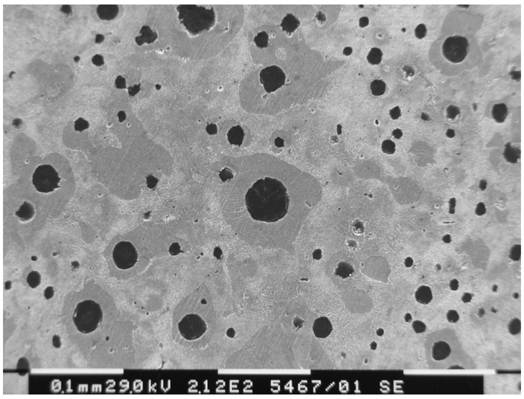
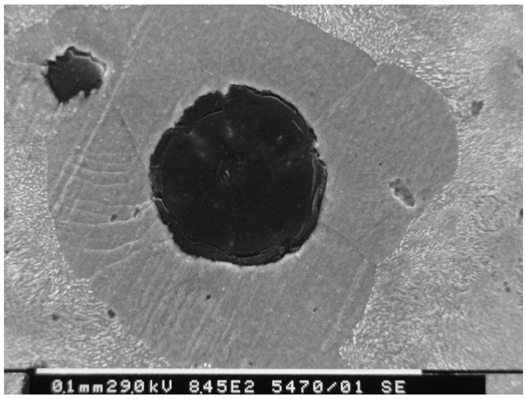


Figure 4: Damaging micromechanisms (σ = 450 MPa): Microcrack propagation in the graphite nodule (a); Graphite nodule – ferritic matrix debonding (a, b).



(a)



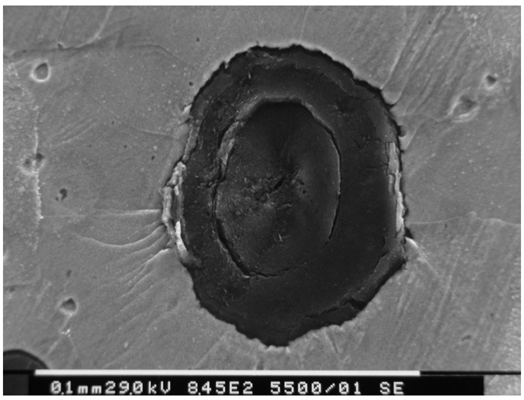
(b)

Figure 4: Damaging micromechanisms (σ = 450 MPa): Slip bands emanating from the graphite nodule and cracks inside the the graphite nodule (a, b: different magnifications).

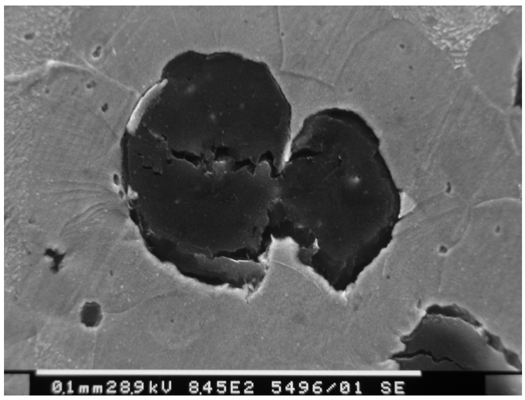
Cracks can initiate and propagate inside the graphite nodules according to two different micromechanisms:

- Cracks initiate corresponding to the nodule center (Fig. 3b), probably corresponding to a solidification site (e.g., a non metallic inclusions) and propagate with a progressive disaggregation of the graphite nodule;
- Cracks initiate and propagate inside the graphite nodule (Fig. 4b), with an external graphite shield and an internal nucleus that become more and more evident with the increase of the macroscopic deformation

The second micromechanism has been already observed in ferritic DCIs and it has been called "onion-like" mechanisms: in ferritic DCIs it seems to be connected to the presence of a mechanical properties gradient inside the graphite nodules, with an outer shield that is characterized by higher nanohardness and wear resistance values with respect to an inner nucleus [12]. Up to now, no nanohardness tests have been performed on the investigated DCI, but the observed damage morphology is similar between ferritic and ferritic-pearlitic DCI, and it is possible to hypothize the presence of an analogous mechanical properties gradient inside the graphite nodules also in the ferritic-pearlitic DCIs.
Near the final rupture, all the damaging micromechanisms in graphite nodules are completely developed (both the "onion-like" mechanism, Fig. 5a, and the "disaggregation" one, Fig. 5b) and some short cracks propagate in the ferritic shield, initiating corresponding to the graphite nodules equator (Fig. 6).



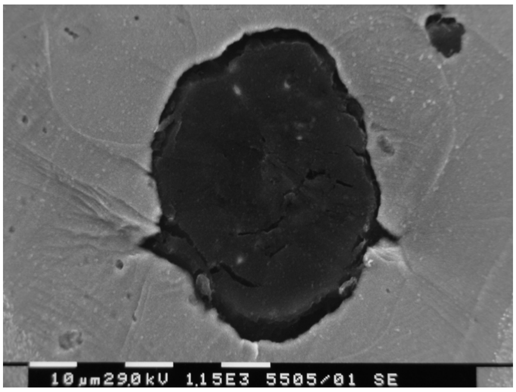
(a)



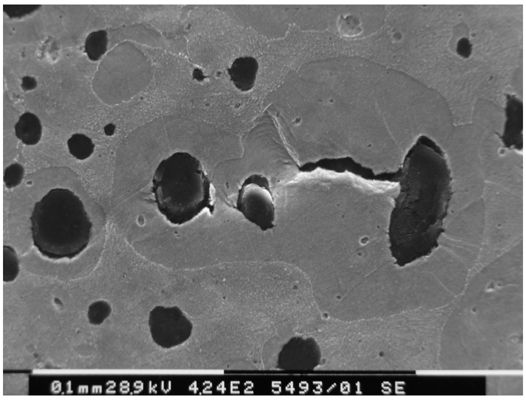
(b)

Figure 5: Damaging micromechanisms (σ = 500 MPa): (a) "onion-like" mechanism with ferrite-graphite debonding and slip bands in the ferritic shield; (b) internal crack propagation and opening ("disaggregation" mechanism) with slip bands in the ferritic shield (to be compared to Fig. 4a).

Focusing Fig. 5a, it is worth to note the presence of two developed "onion-like" features: the inner is more evident and is almost completely developed; the outer is less evident and is not completely developed. This damaging morphology has not been observed in ferritic DCIs, where the "onion-like" mechanism is more frequent, but is characterized by the presence of a graphite nucleus and only one graphite shield. Nanoindentation tests are necessary in order to analyze the presence of a gradient of mechanical properties in the graphite nodules: considering the observed damaging micromechanisms, it is possible to hypothize the presence of a mechanical properties gradient (analogously to ferritic DCIs), probably due to the solidification mechanisms (with an inner nucleus obtained directly from the melt and an outer shield obtained during the cooling stage and due to the solid diffusion of the carbon atoms through the austenite shield around the graphite nodules.



(a)



(b)

Figure 6: Damaging micromechanisms (σ = 500 MPa): (a) cracks initiation in ferritic shield; (b) crack propagation in ferritic shield.

The increase of the macroscopic deformation implies the propagation of the micro-cracks in ferritic shield, their coalescence and the consequent final rupture of the specimen.
Comparing the damaging micromechanisms observed in the ferritic-pearlitic DCI with the ones observed in fully ferritic and fully pearlitic DCIs, it is possible to summarize the considerations of Tab. 2 [11, 14].

	Ferritic DCI	Ferritic-pearlitic DCI	Pearlitic DCI
Damage observation in the elastic stage	Not observed	Observed	Observed
Matrix – graphite nodule debonding	Never observed	Observed (often with other damaging micromechanisms)	Observed
Cracks initiation and propagation corresponding to the center of the specimen	Observed	Observed	Observed
"Onion-like" mechanism	Observed (maybe the most active mechanism)	Observed (both with one and with two graphite shields)	Observed
Slip band emanating from the graphite nodule equator	Observed (really evident)	Observed in the ferritic shields	Observed but not too evident
Microcracks initiation at the graphite nodule –matrix interface	Observed (but not so frequently)	Observed (no cracks in the pearlitic matrix have been observed)	Observed (together with cracks that initiate far from the nodules; to be verified)

Table 2: Matrix microstructure influence on the damaging micromechanisms.

According to Tab.2, it is evident that:

- Different DCIs matrix microstructure implies the activation of different damaging micromechanisms, or, at least, a different importance of the observed damaging micromechanisms;
- The role played by graphite nodules is more complex than a mere "microvoids initiation and growth" (probably due to the presence of an internal mechanical properties gradient);
- Slip bands accumulation corresponding to the nodules equators implies the initiation and propagation of microcracks (especially in ferrite containing DCIs): their coalescence implies the specimen final rupture.

Considering all the micromechanisms described in Tab. 2, it is possible to conclude that graphite nodules can be considered as "microvoids growing in a ductile matrix" only as first approximation and that a new simulation approach should be optimized, taking into account the effective damaging micromechanisms.

CONCLUSIONS

In this paper, the damaging micromechanisms in a ferritic-pearlitic DCI were investigated, mainly focusing the role played by the graphite nodules, but also taking into account the presence of a dual phase microstructure, with ferrite shields around the graphite nodules embedded in a pearlitic matrix. On the basis of the experimental results, the following considerations can be summarized:

- The investigated ferritic-pearlitic DCI does not show the activation of any damaging micromechanism in the elastic stage.
- Graphite nodules are the damaging initiation sites with different damaging micromechanisms (microcracks initiation in the nodule center; "onion-like" mechanism, with up to two graphite shields around a graphite nucleus; ferritic shields – graphite matrix debonding).
- Ferritic shields are characterized by the emanation of slip bands, that become more and more evident with the increase of the macroscopic deformation;
- Corresponding to the higher macroscopic deformation values, it is observed the microcracks initiation corresponding to the interface ferritic shield – graphite nodules; cracks mainly propagate in ferrite
- Final rupture is obtained due to the microcracks coalescence.

REFERENCES

[1] Labrecque, C., Gagne, M., Review ductile iron: fifty years of continuous development, Can. Metall. Quart., 37 (1998) 343-378.
[2] Dong, M.J., Prioul, C., François, D., Damage effect on the fracture toughness of nodular cast iron: part I. Damage characterization and plastic flow stress modeling, Metall. and Mater. Trans. A, 28A (1997) 2245–2254.
[3] Guillemer-Neel, C., Feaugas, X., Clavel, M., Mechanical behavior and damage kinetics in nodular cast iron: part I. Damage mechanisms, Metallurgical and Materials Transactions A, 31 (2000) 3063-3074.
[4] Dai, P.Q., He, Z.R., Zheng, C.M., Mao, Z.Y., In-situ SEM observation on the fracture of austempered ductile iron, Materials Science and Engineering, A319–321 (2001) 531–534.
[5] Liu, J.H., Hao, X.Y., Li, G.L., Liu, G.Sh., Microvoid evaluation of ferrite ductile iron under strain, Materials Letters 56 (2002) 748–755.
[6] Stokes, B., Gao, N., Reed, P.A.S., Effects of graphite nodules on crack growth behaviour of austempered ductile iron, Materials Science and Engineering A 445–446 (2007) 374–385.
[7] Xue, H.Q., Bayraktarb, E., Bathias C., Damage mechanism of a nodular cast iron under the very high cycle fatigue regime, Journal of materials processing technology, 202 (2008) 216–223.
[8] Liu, J.H., Li, G.L., Liu, G.Sh., Hao, X.Y., Damaged evaluation of ferrite ductile iron with electric resistance, Materials Letters, 58 (2004) 1051– 1055.
[9] Iacoviello, F. , Di Bartolomeo, O., Di Cocco, V., Piacente V., Damaging micromechanisms in ferritic–pearlitic ductile cast irons, Materials Science and Engineering A 478 (2008) 181–186. doi: 10.1016/j.msea.2007.05.110
[10] Berdin, C., Dong, M.J., Prioul, C., Local approach of damage and fracture toughness for nodular cast iron, Engng Fract Mech, 68 (2001) 1107–1117.
[11] Di Cocco, V., Iacoviello, F., Cavallini, M., Damaging micromechanisms characterization of a ferritic ductile cast iron. Engineering Fracture Mechanics, 77 (2010) 2016–2023. doi: 10.1016/j.engfracmech.2010.03.037
[12] Di Cocco, V., Iacoviello, F., Rossi, A., Cavallini, M., Natali, S., Ecarla, F., Mechanical properties gradient in graphite nodules: influence on ferritic DCI damaging micromechanisms, Acta Fracturae, (2013) 222-230.
[13] Di Cocco, V., Iacoviello, F., Rossi, A., Iacoviello, D., Macro and microscopical approach to the damaging micromechanisms in a ferritic ductile cast iron, Theoretical and Applied Fracture Mechanics, 69 (2014) 26-33. doi:10.1016/j.tafmec.2013.11.003.
[14] Iacoviello, F., Di Cocco, V., Rossi, A., Cavallini, M., Damaging micromechanisms characterization in pearlitic ductile cast irons, Procedia Materials Science, 3 (2014) 295–300. doi: 10.1016/j.mspro.2014.06.051.