Available online at www.sciencedirect.com

ScienceDirect

Procedia Structural Integrity 3 (2017) 201–207

Structural Integrity Procedia

www.elsevier.com/locate/procedia

XXIV Italian Group of Fracture Conference, 1-3 March 2017, Urbino, Italy

Damaging micromechanisms in an as cast ferritic and a ferritized ductile cast iron

Laura D'Agostino[a]*, Vittorio Di Cocco[a], Diego O. Fernandino[b], Francesco Iacoviello[a]

[a]*Università di Cassino e del Lazio Meridionale, DiCeM, via G. DI Biasio 43, Cassino (FR), Italy*
[b]*INTEMA – Faculty of Engineering, National University of Mar del Plata – CONICET, Av. Juan B. Justo 4302, Mar del Plata, Argentina*

Abstract

Mechanical behavior and damaging micromechanisms in Ductile Cast Irons (DCIs) are strongly effected by matrix microstructure (e.g., phases volume fraction, grains size and grain distribution) and graphite nodules morphology peculiarities (e.g., nodularity level, nodule size, nodule count, etc.). The influence of the graphite nodules depends on both the matrix microstructure and the loading conditions (e.g., quasi-static, dynamic or cyclic loadings). According to the most recent results, these graphite nodules show a mechanical properties gradient inside the graphite nodules, with the graphite elements – matrix debonding as only one of the possible damaging micromechanisms.
In this work, two different ferritic DCIs were investigated (a ferritic matrix obtained from as-cast condition and a ferritized matrix) focusing on the damaging micromechanisms in graphite nodules due to tensile stress. Specimens lateral surfaces were observed using a Scanning Electron Microscope (SEM) during the tests following a step by step procedure.

Keywords: Ductile cast irons (DCIs); Tensile test; Graphite nodules; Damaging micromechanisms.

Introduction

Ductile cast irons (DCIs) are characterized by the presence of free graphite with a nodule shape obtained by means of a chemical composition control instead of extended annealing treatment of white irons as in malleable irons. Thanks to this peculiar graphite shape, instead of lamellae as in grey cast iron, DCIs are able to combine the castability of

---

* Corresponding author. Tel.: +39.07762993681; fax: +39.07762993781.
E-mail address: laura.dagostino@unicas.it

10.1016/j.prostr.2017.04.045

gray irons with toughness of carbon steels. Because of their versatility and their higher performances at lower cost (compared to steels with analogous performances) DCIs are widely used in different applications. Nowadays, DCIs are mainly used in the form of ductile iron pipes (for transportation of raw and tap water, sewage, slurries and process chemicals), in safety related components for automotive applications (gears, bushings, suspension, brakes, steering, crankshafts) and in more critical applications as containers for storage and transportation of nuclear wastes. DCIs matrix controls mechanical properties and matrix names are used to designate spheroidal cast iron types, Jeckins (1993), Ward (1962), Labreque (1998). The most common DCIs grades commercially available are:

- Ferritic DCIs show good ductility and impact properties, with a tensile strength that can be considered equivalent to the values offered by low carbon steel.
- Pearlitic DCIs are characterized by higher strength values, good wear resistance and moderate ductility.
- Ferritic-pearlitic have intermediate properties between ferritic and pearlitic ones.

Focusing on graphite elements shape, a very high nodularity is strongly recommended. The peculiar morphology of graphite elements in ductile irons is responsible of DCIs good ductility and toughness. Graphite nodules act as "crack arresters", with a consequent increase of toughness, ductility and crack propagation resistance. DCIs main damage micromechanism is often identified as voids growth corresponding to graphite nodules and numerous studies provided analytical laws to describe growth of a single void, depending on the void geometries and matrix behaviour, Liu (2002), Liu (2004), Bonora (2005), Iacoviello (2008): as a consequence, spheroids role is completely neglected. Considering almost fully ferritic DCIs, Berdin (2001) proposed that these DCIs should be essentially considered as porous materials, graphite nodules being considered as voids in an elastic–plastic matrix. Microcracks in graphite nodules were also observed, but their presence was not considered as important. Damage main micromechanism was identified with graphite–matrix debonding, and all the other mechanisms were considered as negligible. Recently, Di Cocco (2010 and 2014), especially considering ferritic matrix, the role of the graphite-matrix debonding was reduced, considering the evident contribution to the DCI damage of supplementary damaging micromechanisms. Among them:

- An "onion-like" damage mechanism: nodule shield debonds from nodule core by means of a ductile mechanism; this mechanism is probably connected to a different mechanical behaviour between the nodule "core" (obtained directly from the melt) and the carbon shield (obtained by means of solid diffusion during cooling).
- Radial and transversal cracks initiation and propagation: this damage mechanism is usually more evident corresponding to graphite elements with a reduced roundness; some radial cracks can be also identified in nodule cores, probably corresponding to graphite solidification nucleation sites (e.g., non metallic inclusions like MgS or CaS);

In this work, differences between the damaging micromechanisms in a as cast ferritic and in a ferritized DCIs were investigated by means of step by step tensile tests. Lateral specimens surfaces were analysed by means of Scanning Electron Microscope (SEM) observations during the tests.

2. Investigated material and experimental procedure

Two DCIs were considered with good nodularity:

- An as cast ferritic DCI (chemical composition in Tab. 1; nodularity is higher than 85%);
- a ferritized DCI (chemical composition in Tab. 2; nodularity is higher than 95%).

The second DCI was ferritized by an annealing heat treatment, consisting of an austenitizing stage at 920 °C for 4 h, followed by a slow cooling down to room temperature inside the furnace, Fernandino (2015).

Mini tensile specimens, characterized by a lenght×width×thickness equal to 25×2×1mm, were metallographically prepared and were underwent to tensile tests using a tensile holder (Fig.1). The following step by step procedure was adopted, Di Cocco (2010):

- during the tensile test, the tensile holder (Fig1a) was located in the testing machine (Fig. 1b) and the load was applied using the screw rotated by a step-motor;
- the tensile test was stopped corresponding to different values of the macroscopic deformation and the tensile holder with the stresse specimen was located in the SEM vacuum chamber.
- Lateral surfaces were observed step by step by SEM focusing on the damaging micromechanisms in graphite nodules due to tensile tests.

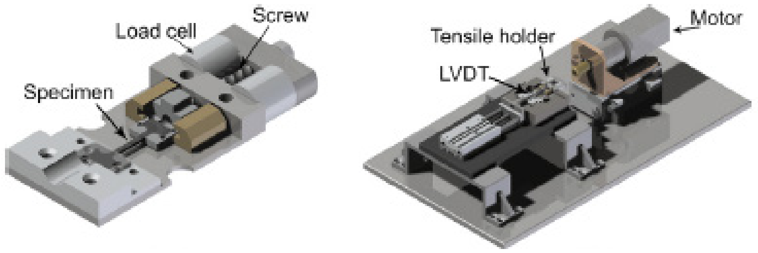
Table 1. Investigated fully ferritic DCI chemical composition.

C	Si	Mn	S	P	Cu	Cr	Mg	Sn
3.62	2.72	0.19	0.011	0.021	0.019	0.031	0.047	0.011

Table 2. Investigated ferritized DCI chemical composition.

C	Si	Mn	S	P	Cu	Cr	Mg	Ni
3.32	2.36	0.31	0.012	0.016	0.62	0.058	0.033	0.025

Applied loads and specimens deformations were measured using, respectively, two miniature load cells (10 kN each) and a Linear Variable Differential Transformer (LVDT).



(a) (b)

Fig. 1. Tensile holder with mini tensile specimen (a) and tensile test machine (b).

3. Experimental results and discussion

Considering the as cast ferritic DCI, Di Cocco (2014), the main damaging micromechanism is the so called "onion-like" mechanism (Figs 2-4). This mechanism, Di Cocco (2013), can be described as an internal debonding between:

- a nodule core, obtained directly from the melt during the solidification process and characterized by lower nanohardness values and lower wearing resistance,
- a nodule shield, obtained during the cooling stage and due to a carbon solid diffusion through the austenitic shield obtained during the eutectic reaction (characterized by higher nanohardness values and a higher wearing resistance).

In addition, a secondary damage mechanism is often observed (Fig. 2 and Fig. 3). After the ''onion-like" mechanism initiation, some secondary cracks could initiate near the nodule centre and propagate with the stress increase ("disgregation" mechanism).

Focusing on the ferritic matrix, the increase of the applied load implies an increase of the presence of slip bands, usually but not uniquely in proximity to the nodule equators, with the initiation and propagation of secondary cracks (Figs 2-4). Secondary cracks propagation and "coalescence" implies the final collapse of the specimen corresponding to the UTS value.

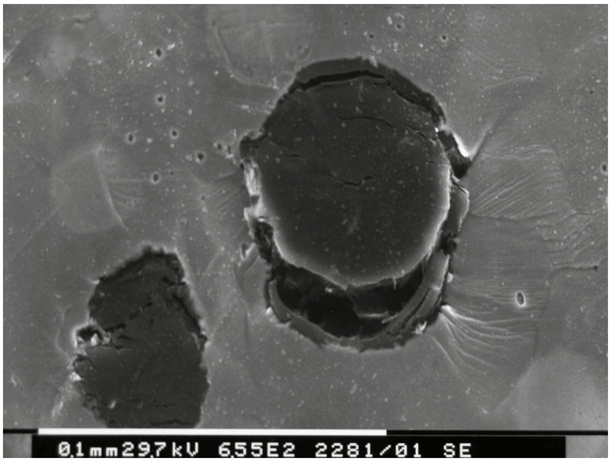


Fig. 2. As cast ferritic DCI. Damaging mechanism (ε% = 14).

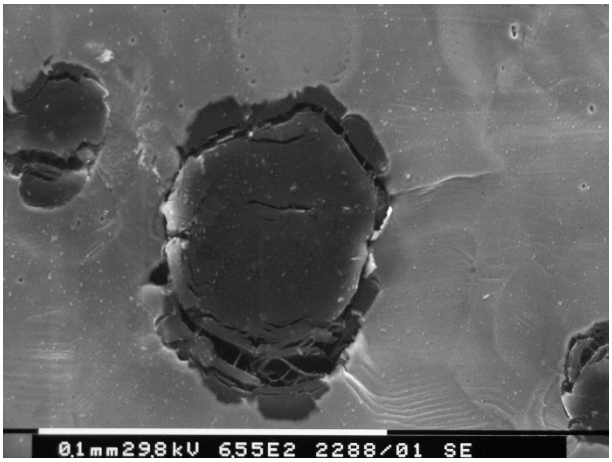


Fig. 3. As cast ferritic DCI. Damaging mechanism (ε% = 14).

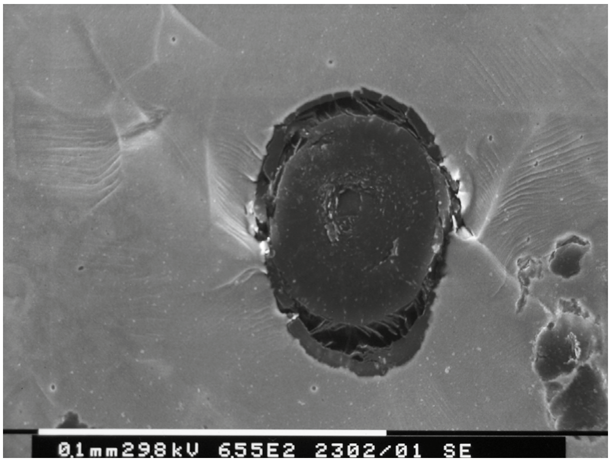


Fig. 4. As cast ferritic DCI. Damaging mechanism (ε% = 14).

Focusing on the ferritized DCI, it is necessary to underline that the ferritization heat treatment implies the activation of carbon atoms solid diffusion from the metal matrix toward the graphite nodules, with a mechanism that is similar to the one that is activated during the grey core malleabilization process. As a consequence, a small increase of the nodule radius and a small modification of the nodule shape with an evident increase of the nodule "roughness" are obtained (Fig. 5), Fernandino (2015).

During the tensile test, the increase of the applied macroscopic deformation (ε%) implies the initiation and propagation of circumferential cracks corresponding to the interface between the "original" nodules (obtained directly in the as-cast conditions) and the thin carbon shields obtained during the ferritization process (Fig. 6 and 7). This mechanism ("secondary onion-like") initiates corresponding to the nodules pole cap and propagates toward the nodules equator with the increase of the macroscopic deformation. This "secondary onion-like" mechanism prevents the activation of the "primary" onion-like mechanism observed in the as cast ferritic DCI between the nodule core and the shield obtained during the cooling stage. The initiation and growth of secondary cracks inside the nodules is almost negligible.

Considering the ferritized matrix, the presence of slip bands become more and more evident with the increase of the applied deformation. Secondary cracks initiates at the interface between the graphite elements and the ferritized matrix, mainly corresponding to the higher roughness zones. The density of these secondary cracks seems to be higher than the density observed in the as cast ferritic DCI, although this should be confirmed by further experimental results (Fig. 8).

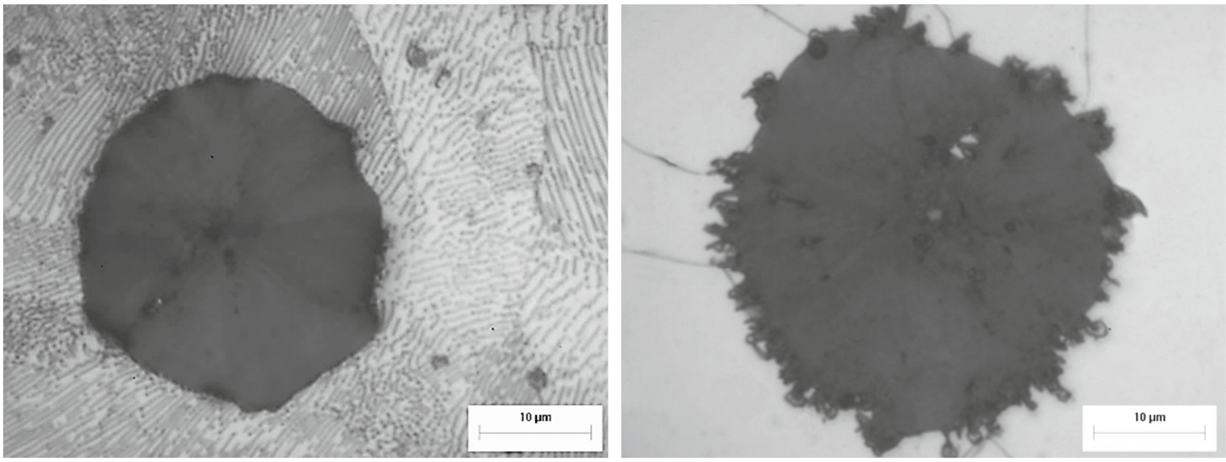


Fig. 5. Ferritized DCI. Nodules morphology before (left) and after (right) ferritizing heat treatment.

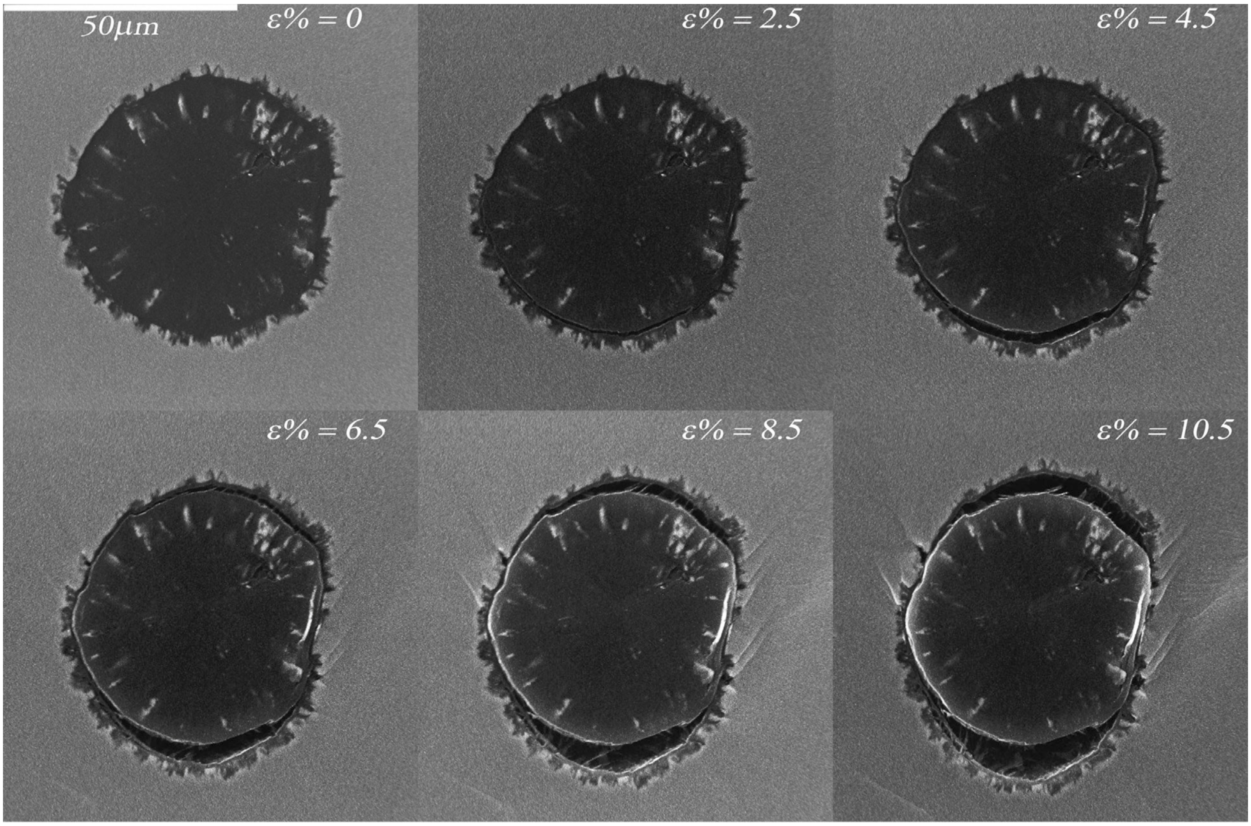


Fig. 6. Damaging mechanisms in ferritized DCI (different strain values).

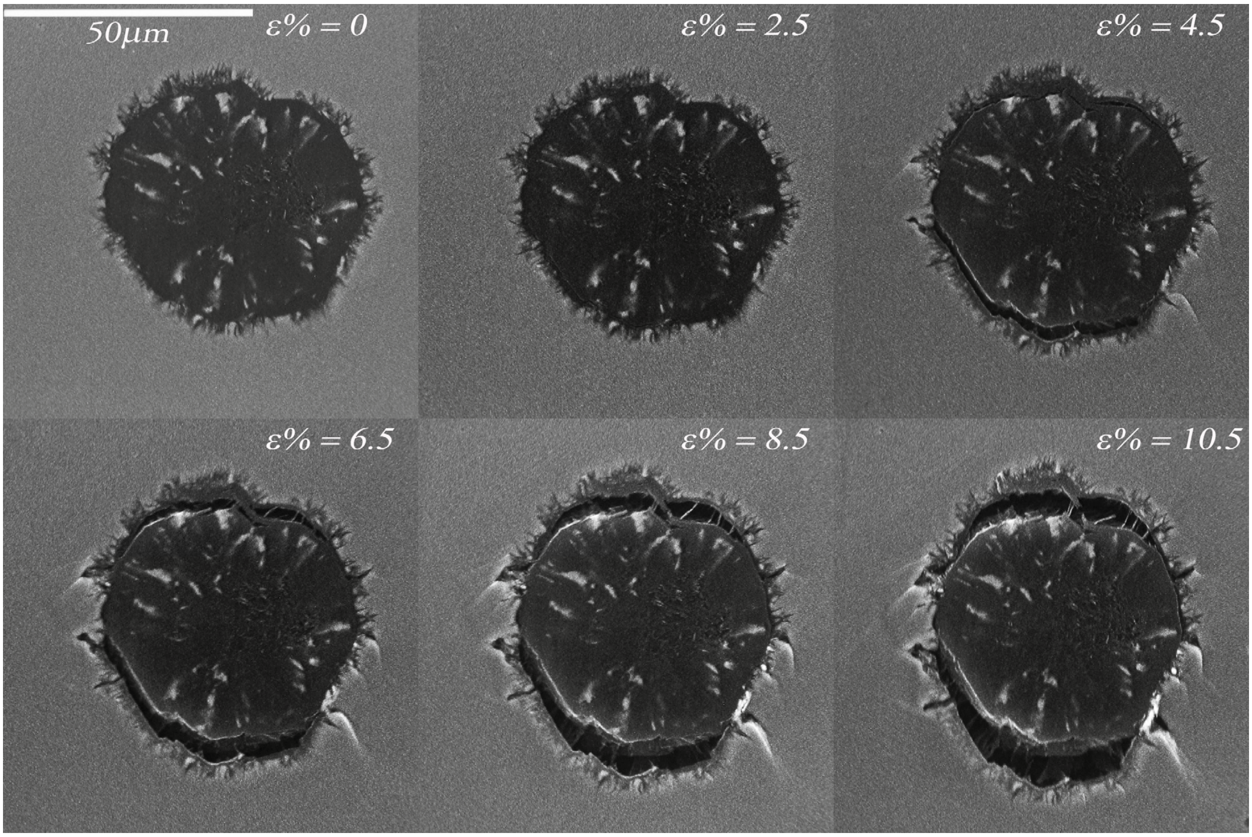


Fig. 7. Damaging mechanisms in ferritized DCI (different strain values).

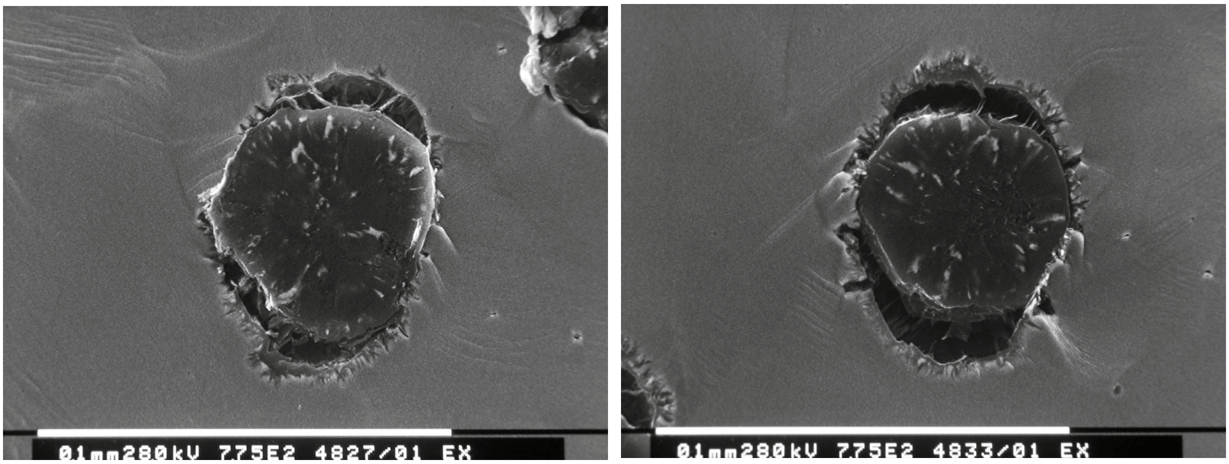


Fig. 8. Ferritized DCI. Damaging mechanisms in graphite nodules and in the ferritic matrix.

Conclusions

In this work, the damaging micromechanisms during a tensile test were investigated considering two DCIs: an as cast ferritic DCI and a ferritized grade. The experimental analysis was performed by means of a step by step procedure, observing the specimens lateral surfaces by means of a scanning electron microscope. According to the experimental results, the following conculsions can be summarized:

- The as cast ferritic DCI damaging mechanism is mainly characterized by an internal debonding between the nodule core (obtained directly form the melt) and the nodule shield (obtained during the cooling stage). This "onion-like" mechanism occurs together with the initiation and propagation of secondary cracks near the nodule center. Corresponding to the higher macroscopic deformation level, slip bands become more and more evident in the ferritic matrix with the iniziation and propagation of secondary cracks.
- The ferritization heat treatment implies a modification both of the dimension and of the shape of the graphite nodules due to a carbon atoms solid diffusion mechanism;
- The ferritized DCI damaging mechanism is characterized by the debonding of the "original" nodules (obtained directly in the as-cast conditions) and the thin carbon shields obtained during the ferritization process. This "secondary onion-like" mechanism prevents the activation of the "primary" onion-like mechanism observed in the ferritic DCI. Slip bands and secondary cracks in the ferritized matrix are more and more evident with the increase of the applied deformation.

References

Berdin, C., Dong, M.J., Prioul, C., 2001. Local approach of damage and fracture toughness for nodular cast iron. Eng. Fract. Mech.. 68, 1107-1117.

Bonora, N., Ruggero, A., 2005. Micromechanical modeling of ductile cast iron incorporating damage. Part I: Ferritic ductile cast iron. Int. Journal of Solids and Structures. 4, 1401-1424.

Di Cocco, V., Iacoviello, F., Cavallini, M., 2010. Damaging micromechanisms characterization of a ferritic ductile cast iron. Engineering Fracture Mechanics. 77, 2016-2023.

Di Cocco, V., Iacoviello, F., Rossi, A., Cavallini, M., Natali, S., Ecarla, F., 2013.Mechanical properties gradient in graphite nodules: influence on ferritic DCI damaging micromechanisms. Acta Fracturae. 222–230.

Di Cocco, V., Iacoviello, F., Rossi, A., Iacoviello, D., 2014. Macro and microscopical approach to the damagin micromechanisms analysis in a ferritic ductile cast iron. Theoretical and Applied Fracture Mechanics. 69, 26-33.

Fernandino, D. O., Cisilino, A. P., Boeri, R. E., 2015. Determination of effective elastic properties of ferritic ductile cast iron by computational homogenization, micrographs and microindentation tests. Mechanics of Materials. 83, 110-121.

Iacoviello, F., Di Bartolomeo, O., Di Cocco, V., Piacente, V., 2008. Damaging micromechanisms in ferritic–pearlitic ductile cast irons. Mater. Science and Engineering A. 478, 181-186.

Jeckins, L.R., Forrest, R.D., 1993. Properties and selection: iron, steels and high performance alloys. ASM Handbook Ductile Iron, Metal Park (OH) ASM International. 1, 35.

Labrecque, C., Gagne, M., 1998. Review ductile iron: fifty years of continuous development. Can. Metall. Quart. 37, 343–378.

Liu, J.H., Hao, X.Y., Li, G.L., Liu, G. Sh., 2002. Microvoid evaluation of ferrite ductile iron under strain. Materials Letters 56, 748-755.

Liu, J.H., Li, G.L., Liu, G. Sh., Hao, X.Y., 2004. Damaged evaluation of ferrite ductile iron with electric resistance. Materials Letters. 58, 1051-1055

Ward, R.G., 1962. An Introduction to the Physical Chemistry of Iron and Steel Making. Arnold, London.