# Analysis of stress triaxiality influence: ferritic DCI damaging micromechanisms

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**ABSTRACT.** Ductile cast irons are characterized by an interesting mechanical properties combination (high ductility, high tensile strength, good wear resistance). Graphite nodules morphological peculiarities and matrix microstructure (both chemical composition and heat treatment controlled) strongly affect the mechanical behaviour and the damaging micromechanisms, also considering very simple loading conditions (e.g. tensile test conditions). Focusing ferritic ductile irons, matrix - graphite nodule debonding is often identified as the main damaging micromechanism, and numerous studies provided analytical laws to describe growth of a single void, depending on the void geometries and matrix behaviour. In this work, ferritic DCI damaging micromechanisms were investigated, under uniaxial tensile tests, considering the triaxiality influence.

**SOMMARIO.** Le ghise sferoidali sono caratterizzate da un'interessante combinazione delle proprietà meccaniche, (elevata duttilità, elevata resistenza meccanica, buona resistenza all'usura). Le peculiarità morfologiche degli elementi di grafite e la microstruttura della grafite (dipendente sia dalla composizione chimica che dal trattamento termico) influenzano notevolmente il loro comportamento meccanico ed i micromeccanismi di danneggiamento. Considerando le ghise sferoidali a matrice ferritica, il principale meccanismo di danneggiamento è stato spesso identificato con il distacco degli sferoidi dalla matrice: numerosi studi hanno proposto quindi delle relazioni analitiche finalizzate alla descrizione della crescita del singolo vuoto generato dal distacco matrice – sferoide, considerando la geometria del vuoto ed il comportamento della matrice. In questo lavoro è stata analizzata l'evoluzione dei meccanismi di danneggiamento di una ghisa sferoidale ferritica sottoposta ad una prova di trazione, considerando l'influenza della triassialità.

**KEYWORDS.** Ductile cast irons; Damaging micromechanisms; Triaxiality.

## INTRODUCTION

DCIs damage micromechanisms analysis is often focused on voids nucleation and growth due to the matrix-graphite nodules debonding [1-5] and numerous studies provided analytical laws to describe a single void growth, depending on the void geometries and matrix behaviour. According to this approach, DCI damage evolution is summarized considering the following stages:

- Separation between nodular graphite and matrix under low stress.
- Plastic deformation in matrix around nodular graphite.
- Initiation of microcracks in deformed matrix between nodular graphite.

- Linkage of graphite elements by microcracks and formation of larger microcracks.
- Linkage of main crack and selected microcracks to form macrocracks.

Focusing the behaviour of a ductile iron with a completely ferritic matrix [3], no damage at graphite nodule interface was observed in the "elastic" part of the load-displacement curve. Few slip lines were observed emanating from the equator of the nodules, indicating a local plastic deformation of the matrix. Decohesions appeared at the pole cap of the nodules when the macroscopic yield stress was reached (Fig. 1a). Increasing macroscopic plastic deformation induced void growth in the stress direction, thus forming ellipsoidal cavities inside which nearly undeformed nodules were embedded (Fig. 1b), and failure occurred by shear instabilities linking adjacent voids.

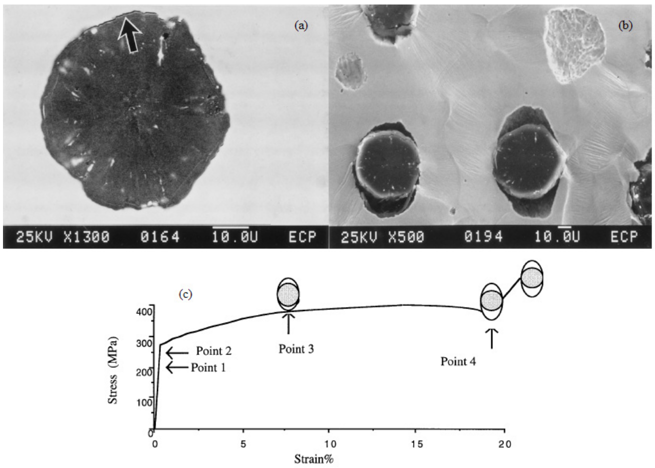

Figure 1: Matrix-graphite nodules debonding evolution during tensile test [3]. a) decohesion of the interface observed in the SEM at point 2 of the stress-strain curve; b) cavity growth around nodules (point 3 of the stress-strain curve SEM observation); c) Stress-strain curve recorded during a tensile test.

More recent experimental results allowed to identify a more complex damaging micromechanism [6-10], with the graphite nodules that do not merely play the role of "debonding initiation point", but are characterized by an internal mechanical properties gradient [11] and show an internal damage development that increases with the increase of the applied macroscopical deformation (Fig. 2).

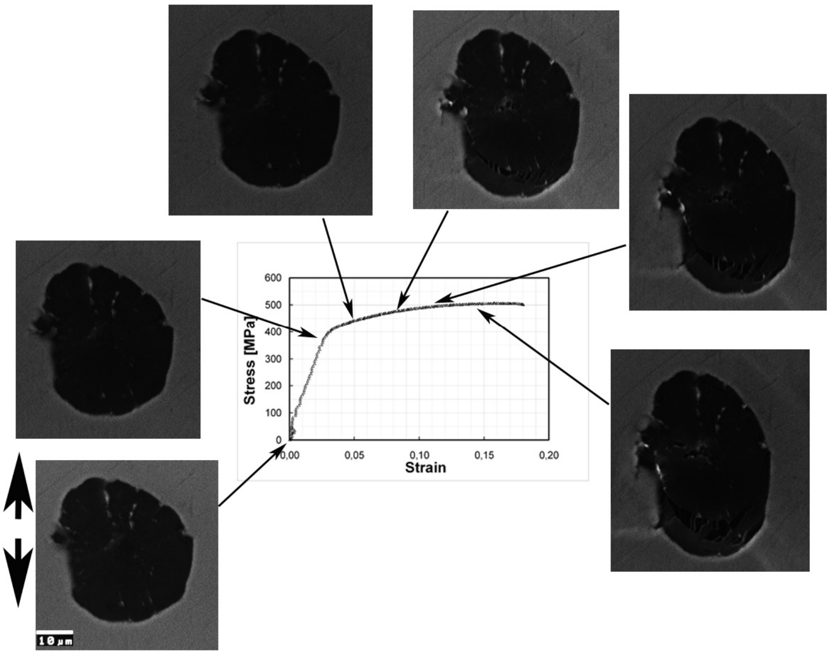

Figure 2: Damage evolution in a ferritic DCI. Role played by the graphite nodules (bold arrows show the loading direction).

According to the experimental results, an "onion like" mechanism is often observed, with a sort of "internal debonding" (Fig. 2). Furthermore, also the initiation and propagation of internal cracks is observed, sometimes corresponding to the nodule center (as in Fig. 2). The graphite nodule – ferritic matrix debonding described in Fig.1 is only seldom observed. Evidences of ferritic matrix plastic deformation (e.g., slip lines) are observed only after the cracks initiation inside the graphite nodule. According to the authors, these mechanisms should be connected to the presence of an internal gradient of mechanical properties inside the graphite nodules, probably due to the different nodule growth mechanisms during the solidification and cooling process, with a possible different distribution of internal defects inside the graphite elements. Furthermore, inside the graphite elements it is often observed the presence of "white spots", as already discussed in [9, 11]. These white spots are not randomly distributed inside the graphite nodules, but are often characterized by a sort of "radial symmetry" and are characterized by a chemical composition that is analogous to the ferritic matrix (considering the main alloying elements). Analyzing the damage evolution in a nodule characterized by an absolutely unusual presence of "white spots" (almost an "exploded graphite"), it is worth to note that these "white spots" do not seem to decrease the nodule mechanical resistance (Fig. 3): although the cracks initiation is observed at the end of the elastic stage (probably due to the stress intensification connected to the not spherical shape of the graphite element), cracks do not initiate or propagate inside or near the metallic particles and the "onion like" mechanism is confirmed as the most important.

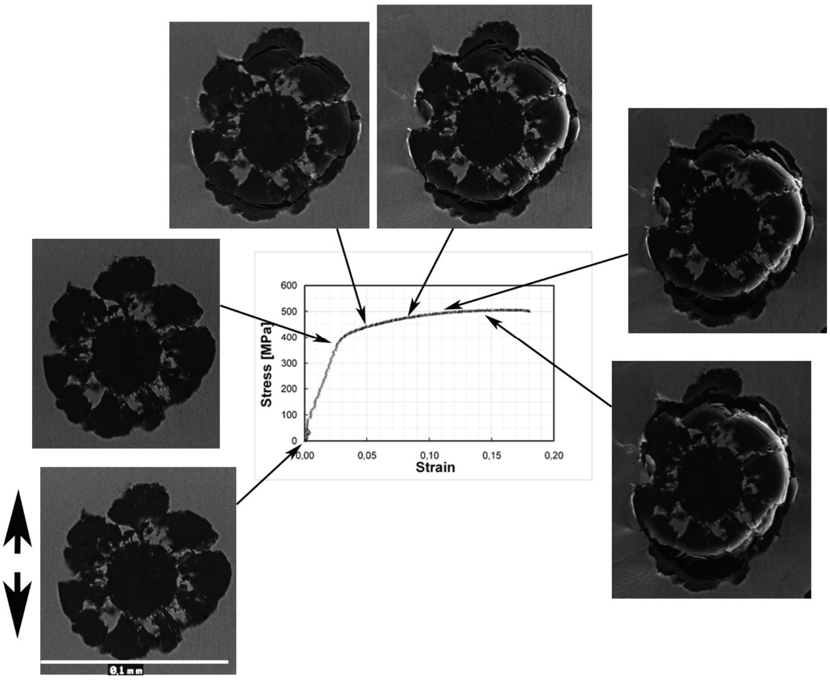

Figure 3: Damage evolution in a ferritic DCI: nodule with high density of "white spots" (bold arrows show the loading direction).

In this work, it is investigated the influence of a high stress triaxiality level on the damaging micromechanisms in a ferritic DCI, by means of tensile tests performed on notched tensile microspecimens, observing the specimens lateral surface during the test by means of a scanning electron microscope and of a digital microscope ("in situ" tests).

## INVESTIGATED MATERIAL AND EXPERIMENTAL PROCEDURES

In this work, a fully ferritic DCI with a high graphite elements nodularity (higher than 85%; 132 nodules/mm$^2$) has been considered (chemical composition in Tab. 1).

| 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 1: Investigated fully ferritic DCI chemical composition (GJS 350-22).

Investigated DCI was cut into microtensile specimens with a length x width x thickness equal to 25 x 2 x 1 mm, respectively, with a central notch (Fig. 4; notch radious R = 2 mm ). Two notched specimens were metallographically prepared. Tensile tests were performed using a tensile holder (Fig. 5): specimens lateral surfaces were observed by means both of a scanning electron microscope (SEM), focusing the damaging micromechanisms in the graphite nodules, and of a Digital Microscope (DM), focusing the damage evolution in the ferritic matrix. Specimens deformation and applied load were measured by means of a Linear Variable Differential Transformer (LVDT) and two miniature load cells (10 kN each), respectively (tensile holder and the fatigue testing machine are shown in Figs 5a and 5b, respectively).

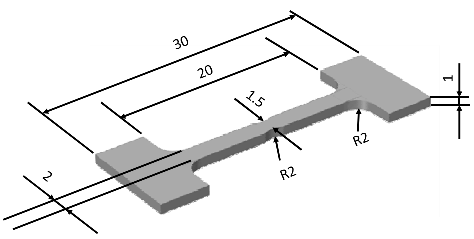

Figure 4: Notched specimen.

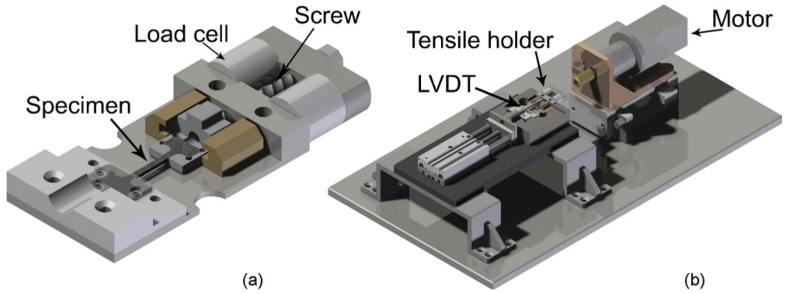

Figure 5: Tensile holder with microtensile specimen (a); tensile testing machine (b).

The stress state and the triaxiality have been evaluated by means of FEM analyses of simulation tests. Model calibration has been performed assuming a continuous isotropic elasto-plastic material behavior. All the calibration parameters have been obtained considering the ferritic DCI macroscopic behavior. Stress state has been evaluated in terms of Von Mises stress and triaxiality has been evaluated by means of Eq. (1), where $\mathrm{tr}(\sigma)$ is the trace of stress tensor and $\sigma_{\mathrm{VM}}$ is the equivalent Von Mises stress [12]:

$$\mathrm{Triax} = \frac{\mathrm{tr}(\sigma)}{\sigma_{\mathrm{VM}}} \tag{1}$$

## EXPERIMENTAL RESULTS AND COMMENTS

### *DM observations*

DM observations allow to analyse the development of the damage in the ferritic matrix during the tensile test. In order to evaluate the stress state on the notched specimen, Von Mises stress analysis was performed considering ferritic DCI as a macroscopically homogeneous and isotropic material and using tensile test results obtained considering standard specimen as constitutive relationship. Fig. 6 shows FEM analysis results corresponding to two different nodules named "1" and "2", with the corresponding crosshead displacement values considered for the DM damage analysis (named as point a, b, c, d, e and f respectively). Points 1 and 2 positions are shown in Fig. 7 and 8, respectively

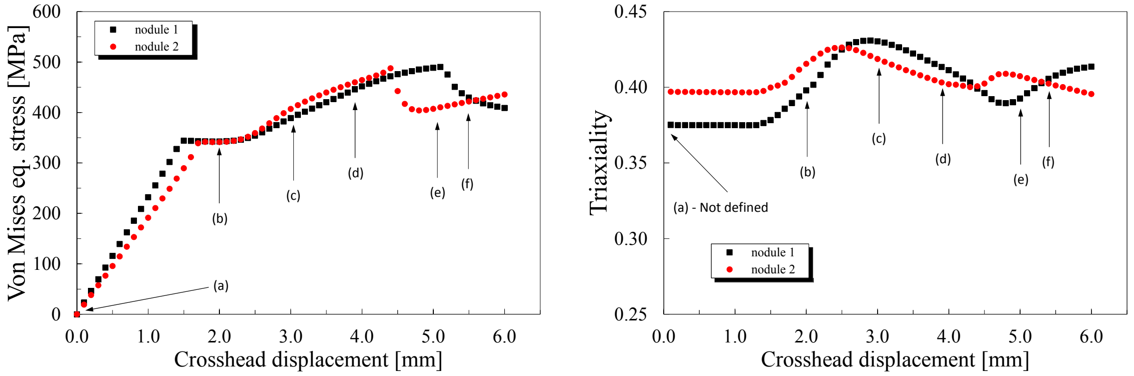

Figure 6: Evolution of Von Mises equivalent stress for two different points in the notched specimen.

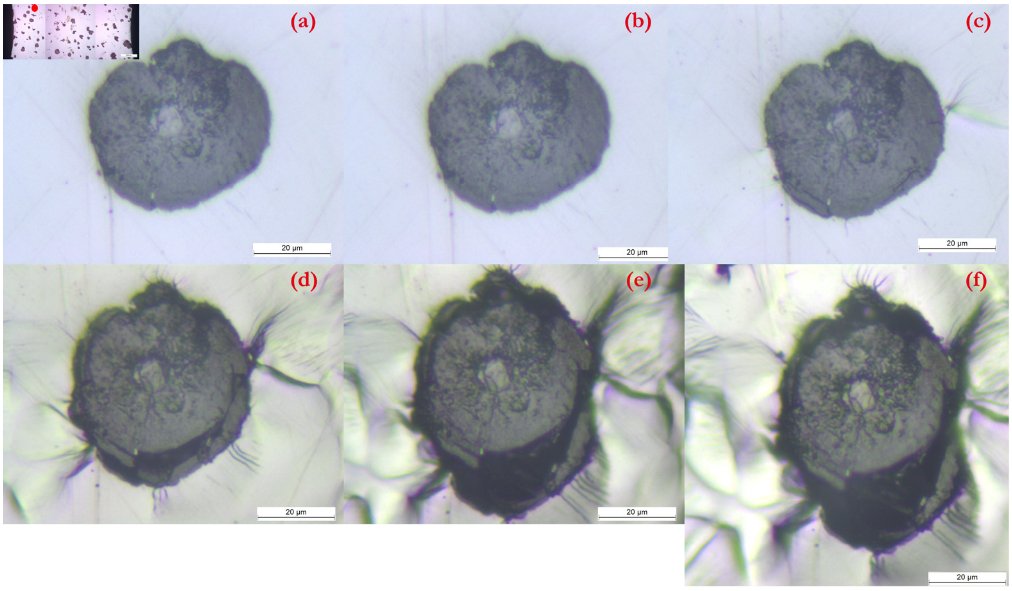

Figure 7: EN GJS350-22 ductile cast iron (nodule 1). DM lateral surface analysis performed on notched specimen (red point indicates the investigated nodule).

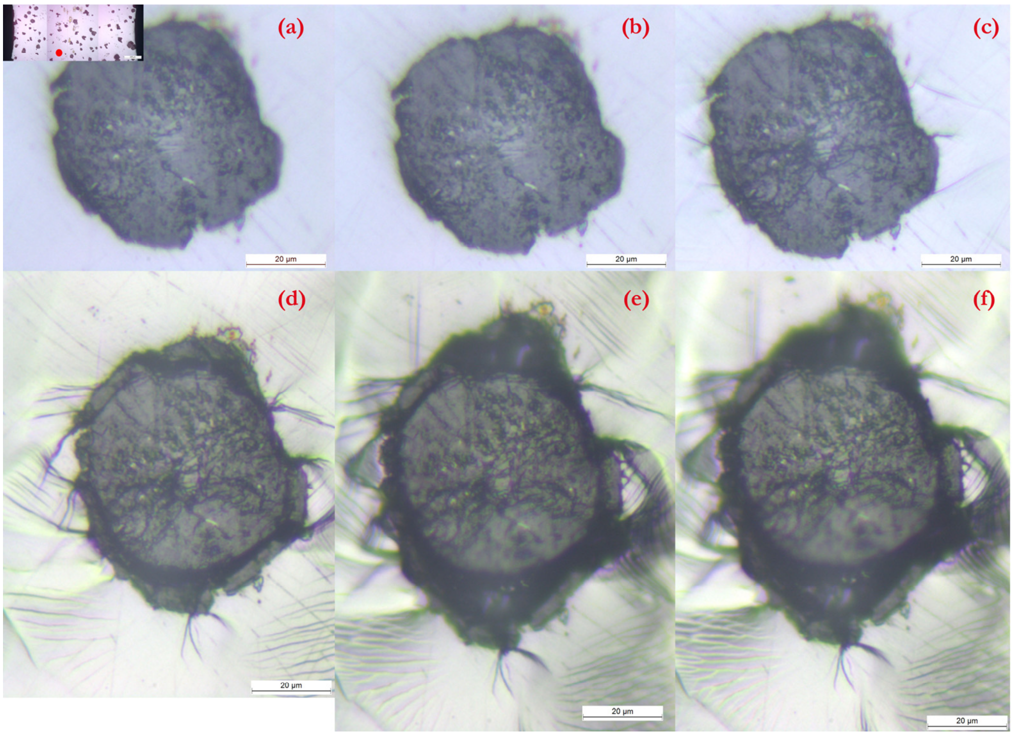

Figure 8: EN GJS350-22 ductile cast iron (nodule 2). DM in situ lateral surface analysis performed on notched specimen (red point indicates the investigated nodule).

The first four steps (from "a" to "d" are characterized by an analogous increase of the Von Mises equivalent stress with the increase of the macroscopic deformation. Focusing the ferritic matrix evolution, it is possible to observe that slip lines mainly generate corresponding to the equator of the nodules (Fig. 7c and 8c) and increase their density with the increase of the deformation, both near the graphite nodules and in the ferritic bulk. The accumulation of these slip lines implies the initiation of microcracks, usually corresponding to the graphite nodule equator. Considering that both Von Mises equivalent stress and Triaxiality evolution with the crosshead diplacement increase are similar in point 1 and 2, it is possible to observe that the damage evolution in the two points is similar. Furthermore, considering the increase of the nodule site eccentricity (defined as the ratio between the minimum axis length / maximum axis length), it is possible to observe that the evolution of this parameter in point 1 and 2 is similar up to the final rupture in Fig. 8f and 9f.

### *SEM observations*

SEM observations are mainly focused on the analysis of the damage corresponding to the graphite nodules during the tensile test. Fig. 9 shows FEM analysis results corresponding to two different nodules named "3" and "4", with the corresponding deformation values considered for the SEM damage analysis (named as point a, b, c, d, e and f respectively).

The "onion like" mechanism is the more evident damaging mechanism, with the initiation that corresponds to the point "c" (Fig. 9-11). The increase of the deformation implies both the microcrack propagation (according to the "onion like" mechanism) and the initiation of new cracks corresponding to the interface between the nodule core obtained directly from the melt and the nodule shield to the carbon solid diffusion through the austenitic shield (during the alloy cooling) [9]. It is worth to note that radial "white spots" (matrix "drops" embedded in graphite nodules [9]) do not play the role of cracks initiation sites.

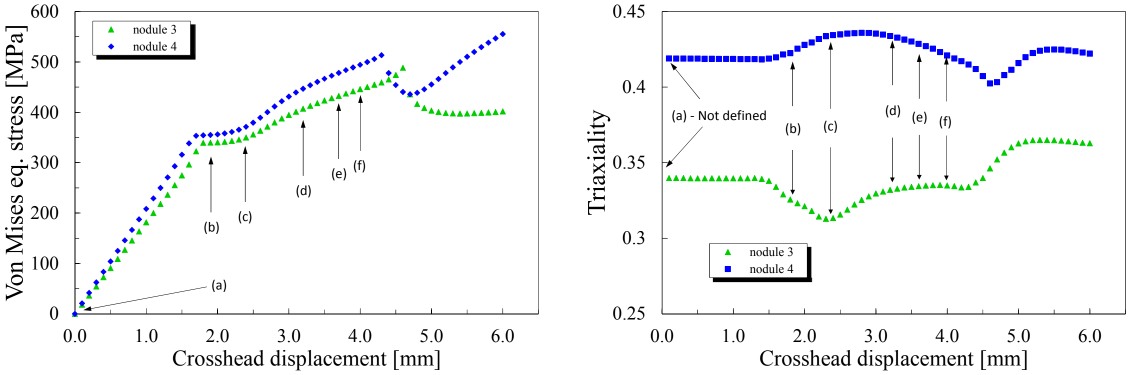

Figure 9: Evolution of Von Mises equivalent stress for two different points in the notched specimen.

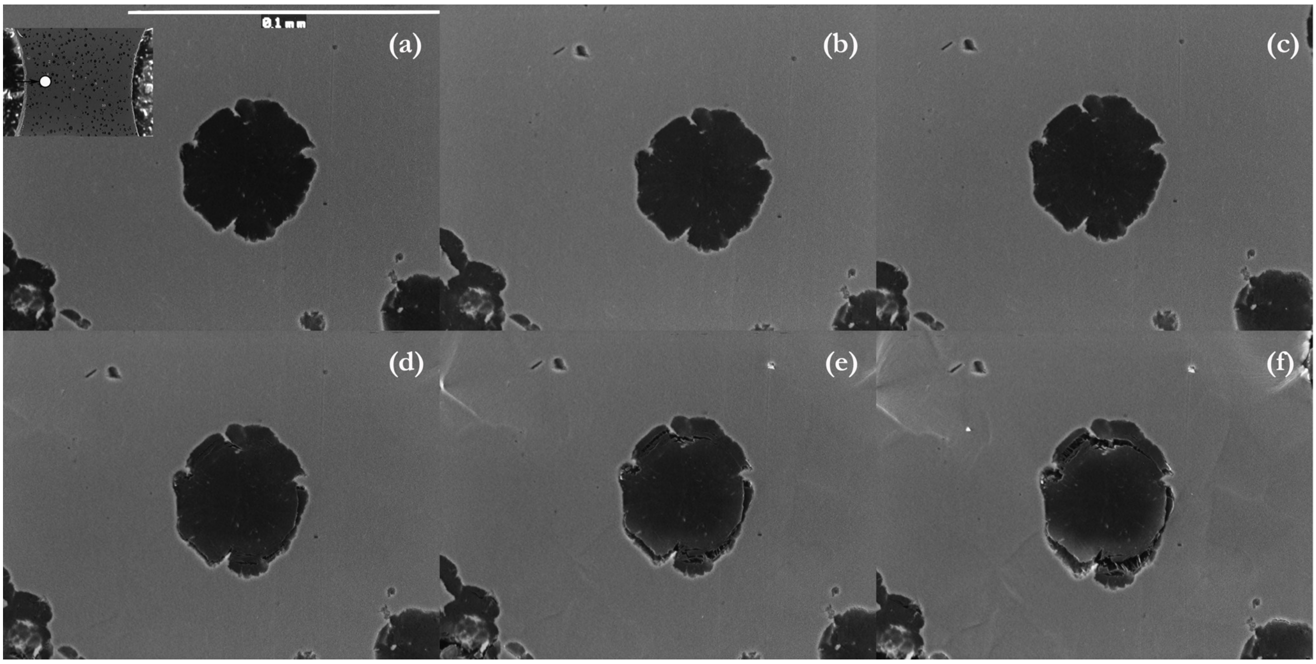

Figure 10: EN GJS350-22 ductile cast iron (nodule 3). SEM in situ lateral surface analysis performed on notched specimen (black point indicates the investigated nodule).

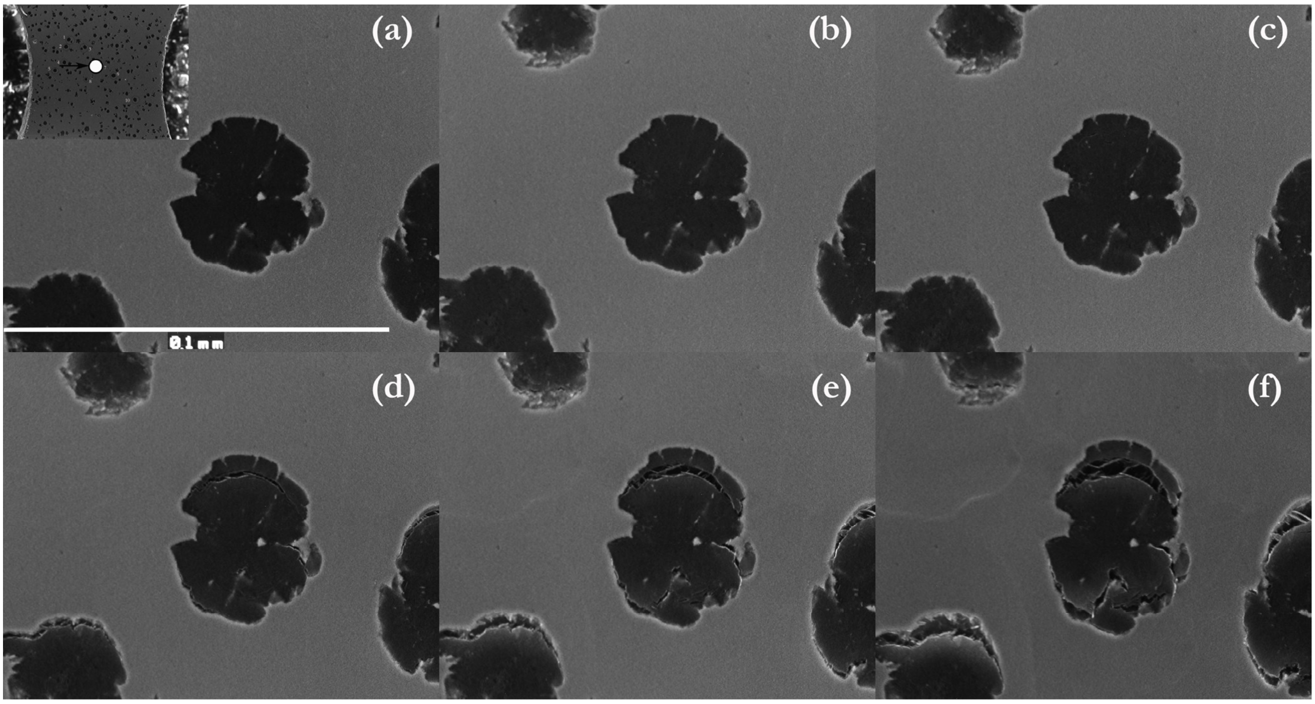

Figure 11: EN GJS350-22 ductile cast iron (nodule 4). SEM in situ lateral surface analysis performed on notched specimen (black point indicates the investigated nodule).

Focusing the FEM results, it is possible to observe that, due to the different investigated positions, the main differences are observed in the diagram "Triaxiality – Crosshead displacement", where nodule 3 is characterised by a lower triaxiality with respect to the nodule 4, for all the measured crosshead displacement values. Considering Fig. 10 and 11, this implies two main consequences:
- higher triaxiality in nodule 4 implies a damage initiation for lower values of the crosshead displacement (Fig. 11c for nodule 4, compared to Fig. 10d for nodule 3)
- higher triaxiality in nodule 4 implies a higher value of the nodule final deformation (Fig. 11f for nodule 4, compared to Fig. 10f for nodule 3).

It is worth to note that analogous triaxiality values trend in nodules 1, 2 and 4 implies analogous values of the final nodule deformation (see Fig. 7f, 8f and 11f).

These results confirm that, considering higher triaxiality conditions, the local deformation, roughly evaluated as the ratio between the minimum axis length / maximum axis length, is higher. Qualitatively observing the local deformation along the cracked specimen (Fig. 12), it is evident (but still not quantified; further experimental activity is necessary) the decrease of the local deformation from the crack surface to the larger specimen section (obviously characterized by a negligible damage).

## CONCLUSIONS

Ferritic DCIs are characterized by good ductility, with tensile strength values that are equivalent to low carbon steels. DCIs are characterized by a composite microstructure: metal matrix with embedded graphite nodules. According to references results focused on the analysis of DCI damaging micromechanisms, the role played by graphite nodules is considered as negligible, identifying graphite nodules – ferritic matric ductile debonding, with the consequent void growth, as the main damaging micromechanisms.

In this work, ferritic DCI damaging micromechanisms were investigated, considering uniaxial tensile tests, and analysing the influence of triaxiality. Step by step tensile tests were performed on unnotched and notched specimens and specimens lateral surfaces were observed by means of a scanning electron microscope (SEM) and a Digital Microscope (DM) during the test ("in situ test"). Different damaging micromechanisms have been observed (mainly "onion like" and, sometimes, crack initiation and propagation in the nodules center) and, corresponding to the higher triaxiality conditions, high local deformation values have been measured.

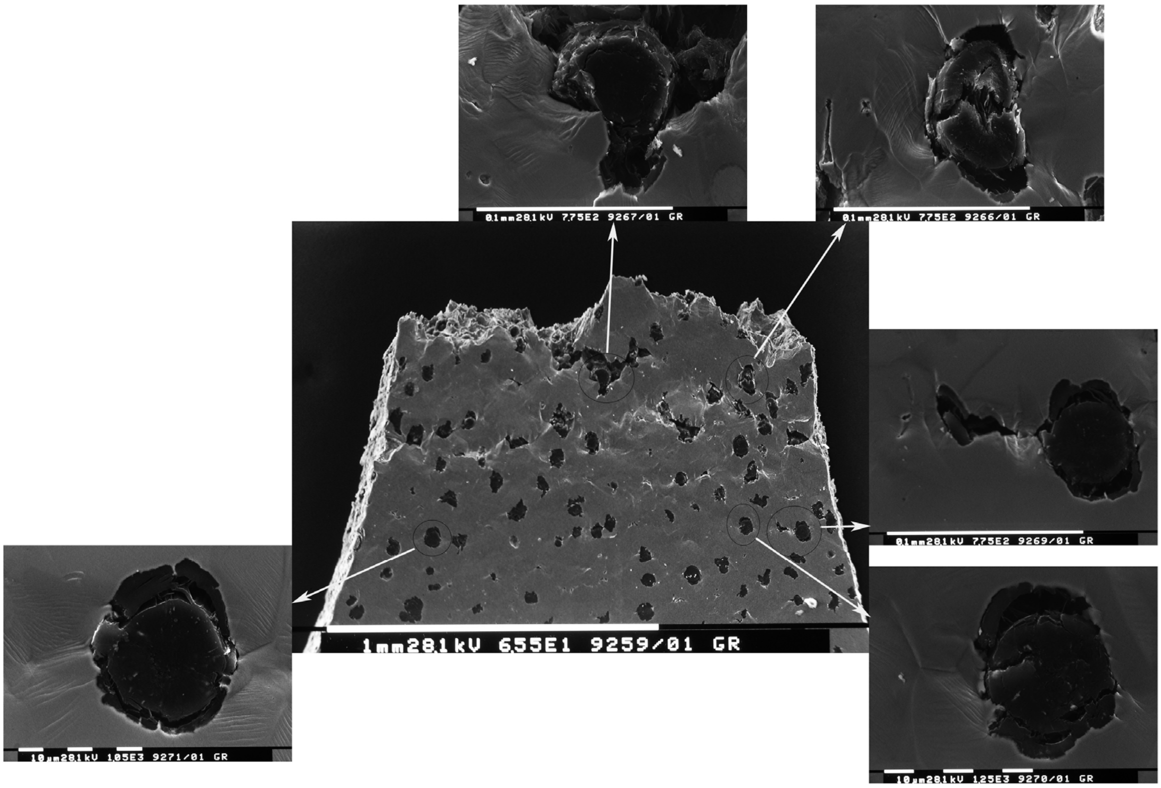

Figure 12: EN GJS350-22 ductile cast iron. SEM in situ lateral surface analysis performed on notched specimen

## REFERENCES

[1] L. M. Eldoky, R. C. Voigt, AFS Trans., 86-104 (1986) 631.
[2] R. C. Voigt, L. M. Eldoky, H. S. Chiou, AFS Trans., 94 (1986) 645.
[3] M. J. Dong, C. Prioul, D. François, Metall. And Mater. Trans. A, 28A, (1997) 2245.
[4] C. Guillermer-Neel, X. Feaugas, M. Clavel, Metall. And Mater. Trans. A, 31A (2000) 3063.
[5] J.H. Liu, X.Y. Hao, G. L. Li, G. Sh. Liu, Mater. Letters, 56 (2002) 748.
[6] F. Iacoviello, V. Di Cocco, V. Piacente, O. Di Bartolomeo, Mater. Science and Engng. A, 478 (2008) 181.
[7] V. Di Cocco, F. Iacoviello, M. Cavallini, Engineering Fracture Mechanics, 77 (2010) 2016.
[8] F. Iacoviello, V. Di Cocco, M. Cavallini, Frattura ed Integrità Strutturale, 13 (2010) 3.
[9] V. Di Cocco, F. Iacoviello, A. Rossi, M. Cavallini, S. Natali, Fatigue & Fracture of Engineering Materials & Structures, (2013, in press).
[10] M. Cavallini, V. Di Cocco, F. Iacoviello, D. Iacoviello, In: Atti del XXI Convegno Nazionale del Gruppo Italiano Frattura (IGF), Cassino, Italy, (2011) 415.
[11] V. Di Cocco, F. Iacoviello, A. Rossi, M. Cavallini, S. Natali, In: XXII Convegno Nazionale del Gruppo Italiano Frattura (IGF), Roma, Italy, (2013) 222.
[12] F. Iacoviello, N. Bonora, D. Gentile, U. Bilardo, In: Atti del IGF 12, Parma, (1996).