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Stress triaxiality influence on damaging micromechanisms in a pearlitic ductile cast iron

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ABSTRACT. In the last decades, damaging micromechanisms in ductile cast irons (DCIs) have been widely investigated, considering both the matrix microstructure and the loading conditions influence. Considering the graphite nodules, they were initially considered as voids embedded and growing in a ductile metal matrix (especially considering ferritic ductile cast irons). Recent experimental results allowed to identify a more complex role played by the graphite nodules, depending on the matrix microstructure.
In this work, damaging micromechanisms in a pearlitic DCI were investigated by means of tensile tests performed on notched specimen, mainly focusing the role played by graphite elements and considering the stress triaxiality influence.

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

INTRODUCTION

DCIs damage micromechanisms analysis was 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 was summarized considering the following stages:
- Separating between nodular graphite and matrix under low stress (matrix-nodule debonding).
- Plastic deformation in matrix around nodular graphite.
- Initiation of microcracks in deformed matrix between nodular graphite.
- Linkage of graphites by microcracks and formation of larger microcracks.
- Linkage of main crack and selected microcracks to form macrocracks.

According to this scheme, graphite nodules are considered as voids embedded in a metal matrix. This approach allows to perform useful simulations of the DCIs mechanical behaviour often described according to Tvergaard Needleman modified Gurson's model [6-8], but it is based on a non-completely correct analysis damaging micromechanisms: only

matrix-graphite debonding is considered and all the other observed damaging micromechanisms are considered as negligible.
Recent experimental results showed that the role played by the graphite nodules is more complex, depending both on the matrix microstructure [9-12] and on the presence of mechanical gradient inside the graphite nodules [13-14], probably due to physical phenomena during the solidification and cooling process. Focusing the triaxiality influence on the damaging micromechanisms and considering ferritic DCIs [15], it is possible to observe that the triaxiality values are not really high and the deformation is mainly developed along the loading directions (Fig. 1 and 2).

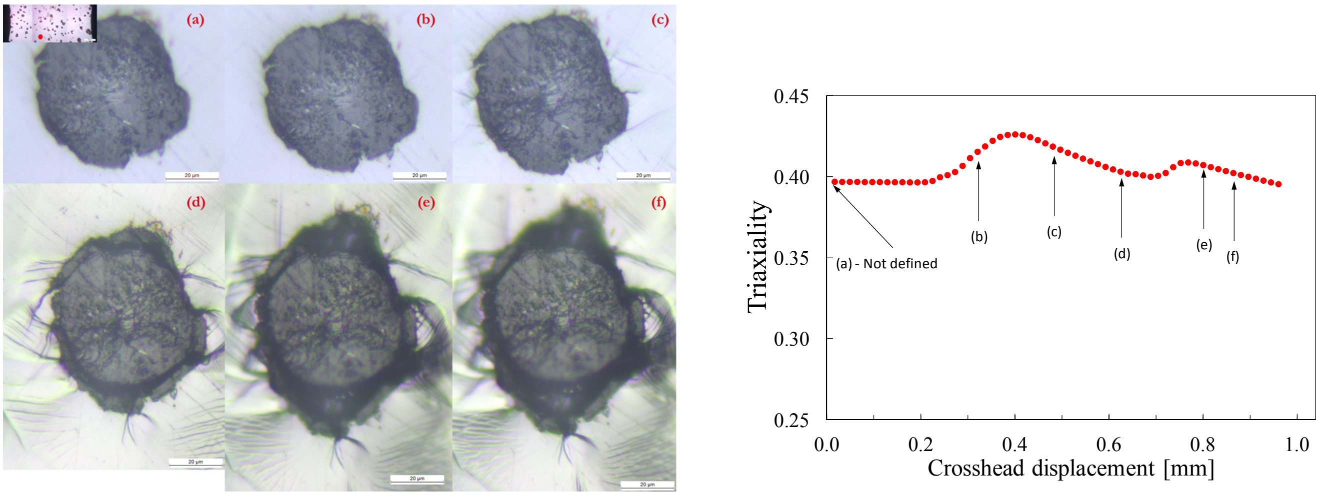

Figure 1: EN GJS350-22 ductile cast iron. Left: Digital Microscope in situ lateral surface analysis performed on notched specimen (red point indicates the investigated nodule). Right: Evolution of the Triaxiality Factor with the crosshead displacement [15].

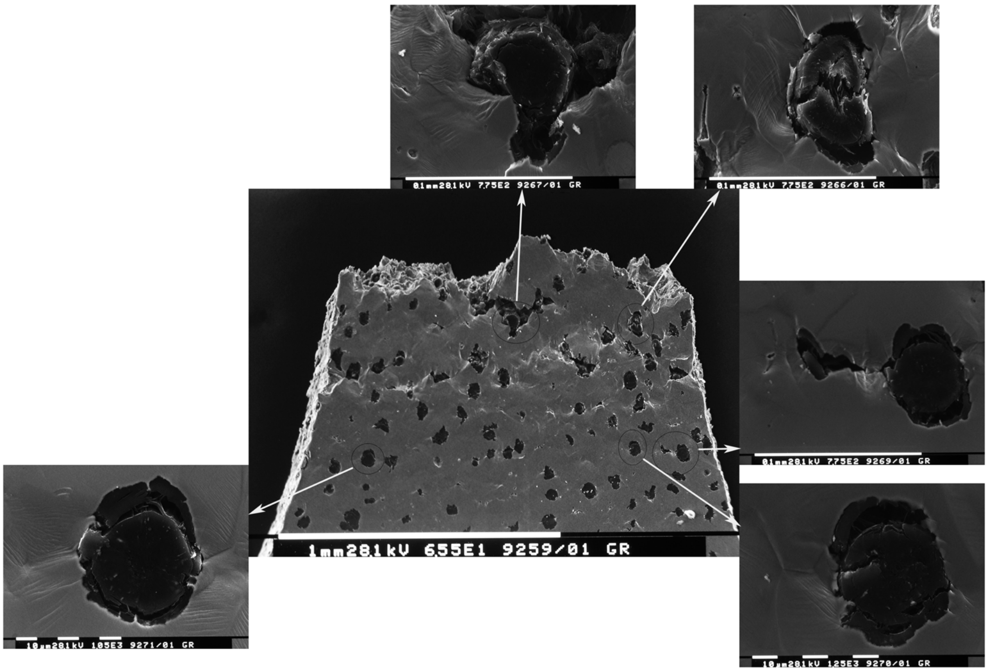

Figure 2: EN GJS350-22 ductile cast iron. Scanning Electron Microscope in situ lateral surface analysis performed on notched specimen [15].

Focusing pearlitic DCIs, and considering smooth specimens [8], they are characterized by the absence of irreversible damage only for very low stress values. An irreversible damage is observed already in the elastic stage, with cracks that initiate and propagate at the graphite nodules pole cap. Cracks initiation and propagation is also observed in the pearlitic matrix. Stress increase implies both cracks propagation in graphite nodules, and matrix plastic deformation with cracks

propagation in pearlitic matrix. Matrix – graphite elements debonding is seldomly observed, with a frequency that seems higher than the one observed in ferritic containing DCIs.
In this work, the influence of a high stress triaxiality level on the damaging micromechanisms in a pearlitic DCI is investigated by means of tensile tests performed on notched tensile microspecimens and observing the specimens lateral surface evolution during the test by means of a scanning electron microscope and of a digital microscope ("in situ" tests).

INVESTIGATED MATERIAL AND EXPERIMENTAL AND NUMERICAL PROCEDURES

In this work, an almost fully pearlitic DCI (5% ferrite) with a high graphite elements nodularity, higher than 85%, with a graphite volume fraction of about 9-10%, was investigated (chemical composition in Tab. 1, %wt).

C	Si	Mn	S	P	Cu	Cr	Mg	Sn
3.59	2.65	0.19	0.012	0.028	0.04	0.061	0.06	0.098

Table 1: Investigated fully pearlitic DCI chemical composition (EN GJS 700-2).

Experimental procedure

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. Three different notch radii were considered, R = 2, 5, 12.5 mm (e.g., Fig. 3; notch radius R = 2 mm). Notched specimens were metallographically prepared (both with and without chemical etching, Nital 1). Tensile tests were performed using with a tensile holder (Fig. 4): 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. The reason of this double observation process is connected to the possibility to use the DM as a portable device, allowing in situ observations.

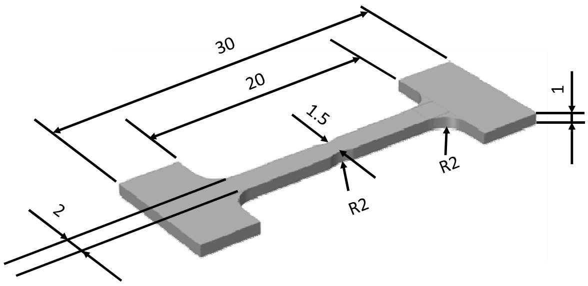

Figure 3: Notched specimen.

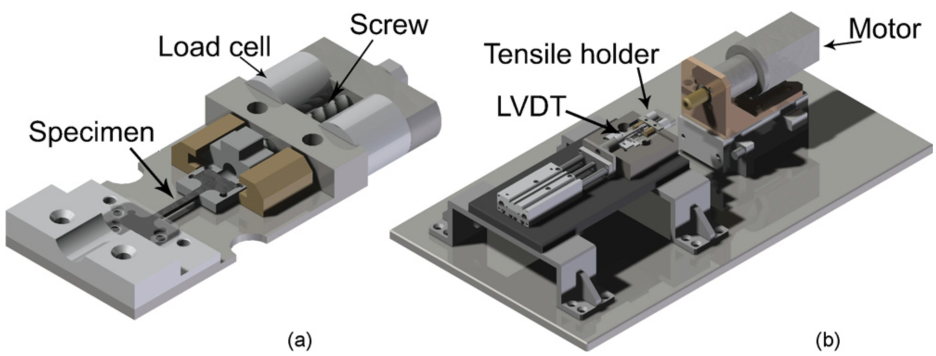

Figure 4: Tensile holder with microtensile specimen (a); fatigue testing machine (b).

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 testing machine are shown in Figs 2a and 2b, respectively). Videos were obtained by means of a morphing commercial software.

Numerical procedure

Stress-Strain curve of the investigated DCI was described by a linear elastic stage characterized by E=160GPa and Poisson ratio υ=0.30 and by an isotropic plasticity model where the yield function was:

$$F = \sigma_{VM} - \sigma_{ys}$$

where σ_{VM} is the equivalent Von Mises stress, and σ_{ys} is the follows isotropic hardening function:

$$\sigma_{ys} = \sigma_{ys0} + \sigma_{b}\left(\varepsilon_{pe}\right)$$

In the isotropic hardening function, σ_{ys0} is the yield stress (for the investigated material σ_{ys0}=430MPa), and $\sigma_{b}\left(\varepsilon_{pe}\right)$ is the hardening function. For the investigated material the hardening function was assumed constant (σ_{b} = 0.08GPa). All the material parameters were evaluated by calibration. The calibration was performed according material parameters simulating the mechanical behavior of an uniaxial GS700 specimen.

Tetrahedral elements were used, characterized by dimensions greater than critical volume of material (about 200 μm) that include nodules and pearlitic grains of the investigate DCI. FEM analysis represents a good approximation at mesoscale of DCI mechanical behavior, but it does not take into account the interaction between structural components like graphite nodules and metallic grains. As a consequence, no stress intensity factor due to interaction of different phases was considered in the FEM analysis. Triaxiality values were evaluated in terms of principal stress by means the Eq. (1) in all investigated nodules positions. Analyses were carried out by simulation of cross-head testing machine displacement. Defining *TF* as a stress Triaxiality Factor parameter:

$$TF = \frac{\frac{1}{3}\cdot\left(\sigma_1 + \sigma_2 + \sigma_3\right)}{\frac{1}{\sqrt{2}}\sqrt{\left(\sigma_1 - \sigma_2\right)^2 + \left(\sigma_2 - \sigma_3\right)^2 + \left(\sigma_3 - \sigma_1\right)^2}} \tag{1}$$

where,

σ_i, i=1, 2, 3 – Principal stresses

Cross head displacement values were used in order to simulate the specimen stress field by using a model which takes in account the stiffness of testing machine.

EXPERIMENTAL RESULTS AND COMMENTS

DM observations

Considering metallographically prepared but not chemically etched specimens, it is possible to observe that the stress increase implies the development of slip bands, mainly generating in correspondence to the nodule equator. The slip bands become more and more evident with the local deformation. Fig. 5 and 6 show the behaviour of two nodules that are characterized by different triaxiality factor TF and Von Mises stress evolutions.

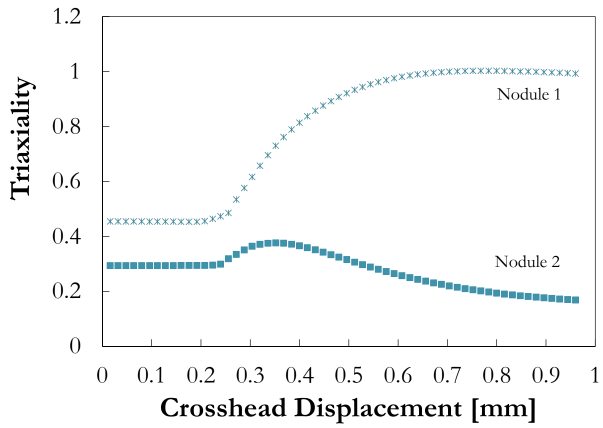

Figure 5: Triaxiality factor evolution with the crosshead displacement.

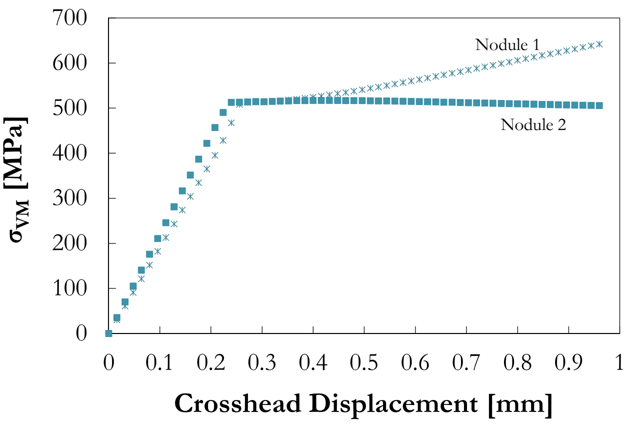

Figure 6: Equivalent Von Mises stress evolution with the crosshead displacement.

Nodule 1 is characterized by the highest TF values (up to 1) and shows a 3D damage development due to the high triaxiality level. The damage initiation (Fig. 7, white arrows) seems to correspond to the increase of the triaxiality factor and it is observed both the debonding between the graphite nodule and the pearlitic matrix and the initiation and growth of internal cracks (so called "onion-like" mechanism). The video shows the damage increase with the equivalent Von Mises stress – crosshead displacement evolution. The DM lateral surface analysis shows a damage that initiates in the graphite nodules and, only for higher values of the equivalent Von Mises stress, shows slip bands. The increase of the slip bands density implies the initiation of microcracks, mainly corresponding to the nodule equator (Fig. 7d and e). Considering other nodules with analogous triaxiality values, it is possible to suppose that graphite – matrix debonding is more important with higher triaxiality values (but this is to be confirmed by further investigations).

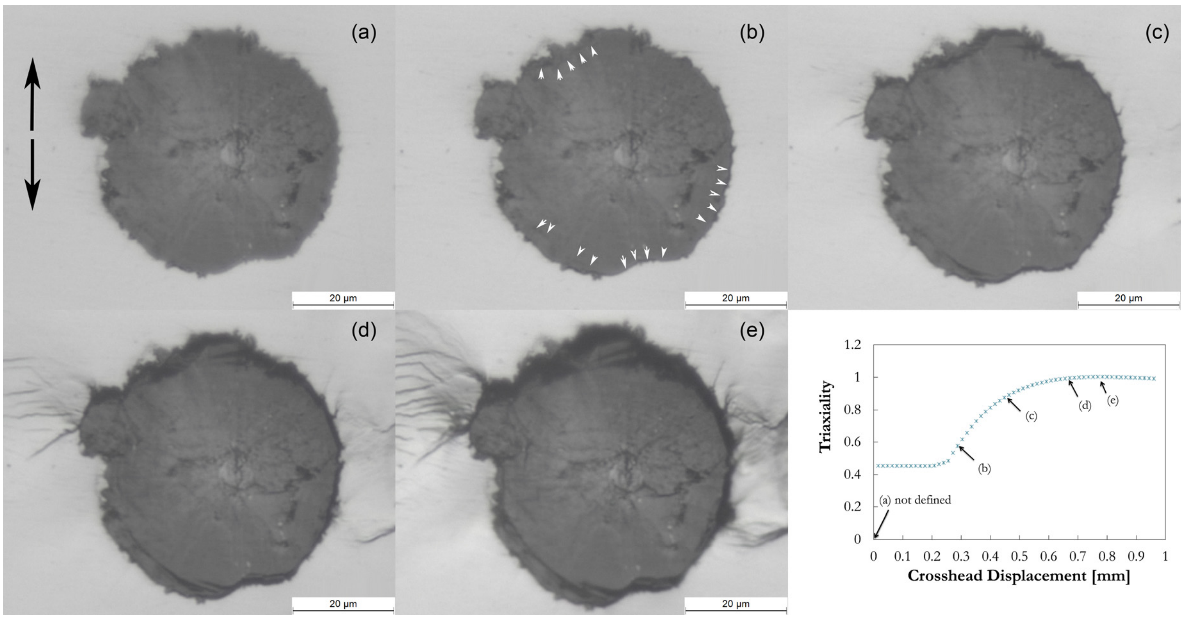

Figure 7: EN GJS700-2 ductile cast iron (Nodule 1, Fig. 5 and 6). Digital Microscope in situ lateral surface analysis performed on notched specimen (a-e); black arrows show the loading direction. Diagram: Triaxiality Factor - Crosshead displacement evolution.

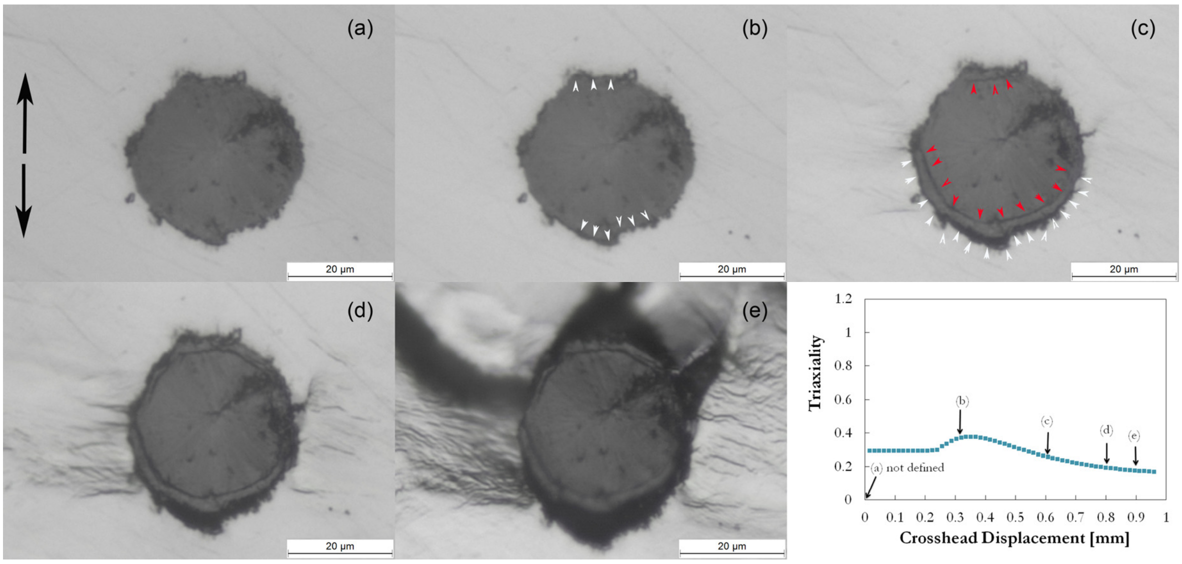

Figure 8: EN GJS700-2 ductile cast iron (Nodule 1, Fig. 5 and 6). Digital Microscope in situ lateral surface analysis performed on notched specimen (a-e); black arrows show the loading direction. Diagram: Triaxiality Factor - Crosshead displacement evolution.

Nodule 2 is characterized by the lowest triaxiality factor values (comparable to the values obtained with the ferritic DCI, Fig. 1). For these conditions, it is possible to describe the damaging evolution according to the following stage:

- Initiation and growth of matrix – graphite nodule debonding (Fig. 8b, white arrows).
- Initiation and growth of the debonding between the "nodule core" and the "nodule shield" ("onion-like" mechanism, red arrows), presence of some slip bands and initiation of short cracks (few microns) in the matrix, Fig. 8c.
- Increase of the slip bands density and growth of the short crack in the matrix, Fig. 8 d.
- Strong increase of the slip bands density and evident increase of the microcracks, Fig. 8e.

Although the matrix is not ductile, the deformation along the loading direction observed in the Nodule 2 is analogous to the one observed in the ferritic DCI (Fig. 1).

SEM observations

SEM observations allow to confirm, with a higher detail, the damaging micromechanisms already observed by means of the DM observations (Fig. 9). The highest deformations along the loading direction are observed for the lowest values of the triaxiality factor.

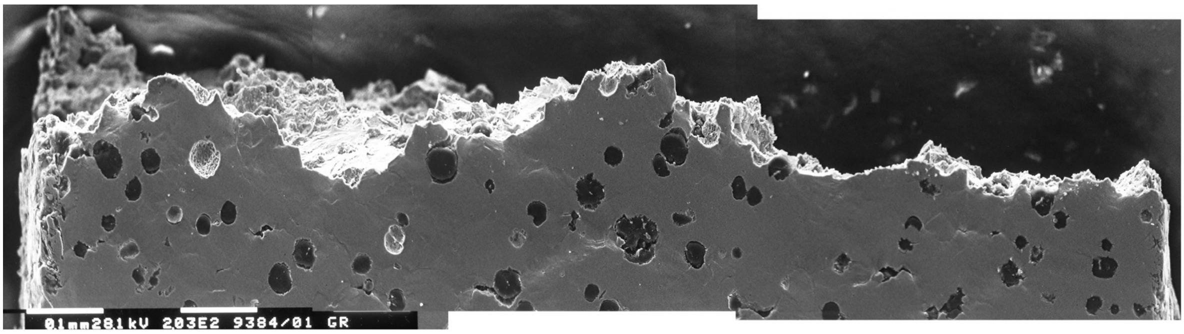

Figure 9: SEM lateral observation of the fracture surface (central notch radious, R = 12.5 mm)

The higher resolution of the SEM analysis allows to identify some further details: focusing the onion like mechanism, it is possible to observe that the microcrack initiation in the "onion like mechanism" can be characterized by a sort of "exfoliation" of the graphite nodule in numerous layers (Fig. 10b).

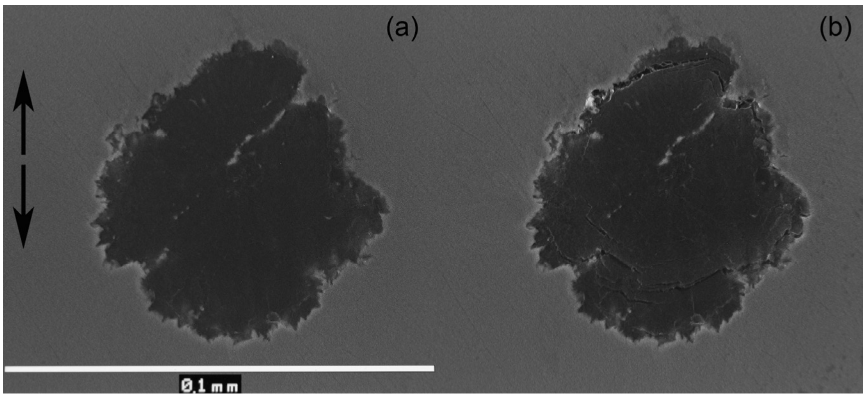

Figure 10: SEM lateral observation of the fracture surface: onion-like mechanism and multiple cracks (black arrows show the loading direction). (a) before the tensile test; (b) during the tensile test.

CONCLUSIONS

In this work, triaxiality influence on damaging micromechanisms in a pearlitic DCI have been investigate by means of tensile tests performed on notched specimens and observations of the lateral surface by means of a SEM and of a DM.

According to the experimental results, the influence of triaxiality on the damaging micromechanisms in a ferritic DCI, it is possible to summarize the following conclusions:

- DM, as a portable device, is able to observe the evolution of the damage in a pearlitic DCI, considering the graphite nodules as privileged, but not unique, observation points;
- Damage is strongly influenced by the triaxiality. It is possible to suppose that nodule – matrix debonding is more important with higher triaxiality values (but this is to be confirmed by further investigations). Anyway, higher triaxiality values correspond to a 3D damage. Lower triaxiality values imply a damage that is mainly developed along the loading direction;
- Slip bands become more and more important with the macroscopic deformation: the interfaces between nodules and matrix are the initiation sites of short cracks that propagate in the matrix.

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