

# Analysis of fatigue damaging micromechanisms in a ferritic ductile iron

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**Abstract.** *Ductile cast irons (DCIs) are characterized by an interesting combination of mechanical properties: first of all, the good castability of gray irons and the toughness of steels. This is due to the peculiar graphite elements shape, obtained by means of a chemical composition control (mainly small addition of elements like Mg, Ca or Ce). Many DCIs microstructures are available: among them, ferritic DCIs are characterized by good ductility, with tensile strength values that are equivalent to a low carbon steel.*

*In this work, fatigue damaging micromechanisms in a ferritic DCI have been investigated by means of in-situ scanning electron microscope observations. Specimens were ground and polished and fatigue loaded by means of an electromechanic testing machine: specimens lateral surfaces were observed “in situ” using a scanning electron microscope (SEM), focusing 20 graphite nodules and considering the ferritic matrix around them. During fatigue 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.*

*On the basis of the experimental results, different fatigue damaging micromechanisms were identified, both in the graphite nodules and in the ferritic matrix.*

## INTRODUCTION

Ductile cast irons (DCIs) were recently discovered (1943) and are characterized by a peculiar shape of graphite elements, with a nodularity obtained through the additions of spheroidizing elements like Mg, Ca, and Ce. It is possible to optimize their mechanical properties by means of the matrix control, and different DCIs are now available [1, 2]:

- Ferritic ductile irons are characterized by good ductility and a tensile strength that are equivalent to a low carbon steel.
- Pearlitic ductile irons show high strength, good wear resistance and moderate ductility.
- Ferritic-pearlitic grades properties are intermediate between ferritic and pearlitic ones.
- Martensitic ductile irons show very high strength, but low levels of toughness and ductility.
- Bainitic grades are characterized by a high hardness.
- Austenitic ductile irons show good corrosion resistance, good strength and dimensional stability at high temperature.
- Austempered grades show a very high wear resistance and fatigue strength.

DCIs versatility, performances and cost are the advantages that have led to their success: they are widely used for water and sewer lines, wheels, gears, crankshafts in cars, truck trailer suspension arm, etc.

In the last decades, damaging micromechanisms analysis in DCI were mainly focused on static or quasi-static loading conditions. The main damage micromechanism was often identified in voids growth corresponding to graphite nodules, cracks nucleation and growth corresponding to graphite nodules – matrix interface, with consequent micro-cracks coalescence generating a

“final” macro crack. According to this proposed micromechanism, graphite nodules are considered as microvoids embedded in a more or less ductile matrix (depending on the microstructure) and numerous studies provided analytical laws to describe growth of a single void depending on void geometry and matrix mechanical behaviour [3-7]. Proposed damaging micromechanism under tensile stress conditions is summarized in Fig. 1.

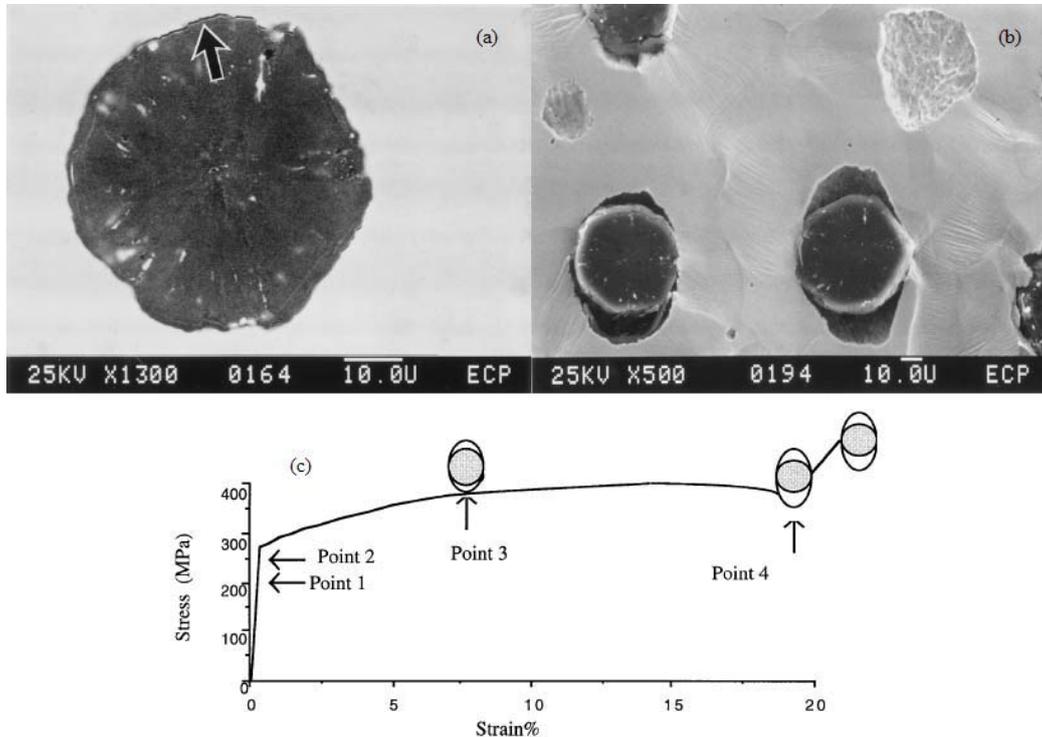


Figure 1. Matrix-graphite nodules debonding evolution during tensile test [3].  
a) decohesion of the interface observed in the SEM at point 2 of the stress-strain curve;  
b) cavity growth around nodules (point 3 of the stress-strain curve SEM observation);  
c) Stress-strain curve recorded during a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

In the last years other experimental activities were developed to define more precisely the damaging micromechanisms in DCIs [8 – 12]. Considering tensile loading conditions and focusing ferritic DCIs, main damaging morphologies could be classified as follows:

- An “onion-like” damage mechanism: nodule shield debonds from nodule core by means of a ductile mechanism; cores diameters are between 75 and 85% if compared to the original graphite spheroids diameters: it is possible to assume 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. High matrix ductility is connected to high graphite spheroids deformation.
- Radial and transversal cracks initiation and propagation: this graphite element damage mechanism usually initiates corresponding to graphite elements with a reduced roundness; some radial cracks initiate in the nodule core, probably corresponding to graphite solidification nucleation sites (e.g., non metallic inclusions like MgS or CaS; they were not observed, probably due to the adopted specimens preparation procedure);
- Interfacial microcracks at the graphite elements – matrix interface are only seldom observed, and their importance seems to be lower than other graphite elements damaging mechanisms.
- Focusing damaging in ferritic matrix, slip bands become more and more evident with the macroscopic deformation increase and, corresponding to very high deformation levels, microcracks initiate and propagate.

An example of damage micromechanisms evolution under tensile loading conditions is shown in Fig. 2.

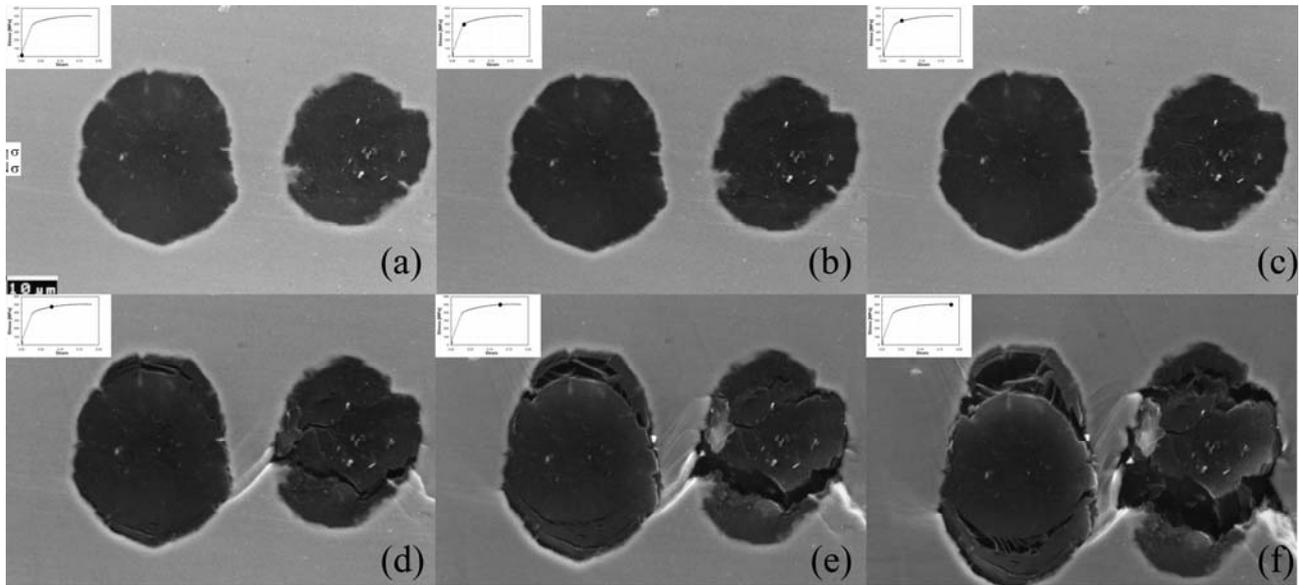


Figure 2: EN GJS350-22 ductile cast iron (100% ferrite). SEM in situ surface analysis corresponding to the following  $\sigma$  [MPa]– $\varepsilon$  % values: (a) 0–0%, (b) 400–2.5%, (c) 430–5%, (d) 470–7.5%, (e) 490–12.5% and (f) 500–17.5%.

DCIs fatigue resistance is usually investigated by means of low cycle fatigue or fatigue crack propagation tests followed by a fracture surface analysis (e.g., by means a scanning electron microscope, SEM). According to these procedures, it is quite complicated to observe the very first stages of the fatigue damaging micromechanisms, focusing both the graphite nodules and matrix role. In this work, microtensile specimens of a fully ferritic DCI were investigated by means of step by step fatigue tests: specimen lateral surfaces were observed in situ by means of a scanning electron microscope (SEM).

## MATERIAL AND EXPERIMENTAL PROCEDURE

A fully ferritic DCI was investigated (chemical compositions is shown in Table 1), with a very high nodularity of graphite elements (higher than 85%) and about 9-10% as graphite elements volume fraction. Investigated DCI was cut into microtensile specimens with a length x width x thickness equal to 25 x 2 x 1 mm, respectively. Specimens were ground and polished and fatigue loaded intermittently with a tensile holder and observed in situ using a SEM, considering 20 graphite elements. During fatigue 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. Figures 3a and 3b show the tensile holder and the tensile test machine, respectively.

Table 1. Ductile cast iron EN GJS350-22 chemical composition (100% ferrite).

C	Si	Mn	S	P	Cu	Cr	Mg	Sn
3.66	2.72	0.18	0.013	0.021	0.022	0.028	0.043	0.010

For each investigated conditions, three fatigue tests were performed under load control conditions, with a loading frequency of 0.03 Hz:

- $\sigma_{\max} = 280$  MPa and  $\sigma_{\min} = 120$  MPa. In order to perform SEM observations, fatigue loading was stopped every 1000 cycles (near final rupture, observation frequency is higher).
- $\sigma_{\max} = 320$  MPa and  $\sigma_{\min} = 120$  MPa. In order to perform SEM observations, fatigue loading was stopped after 1, 20, 40, 60, 80 cycles. Hereafter, observations were performed every 100 cycles (near final rupture, observation frequency is higher).

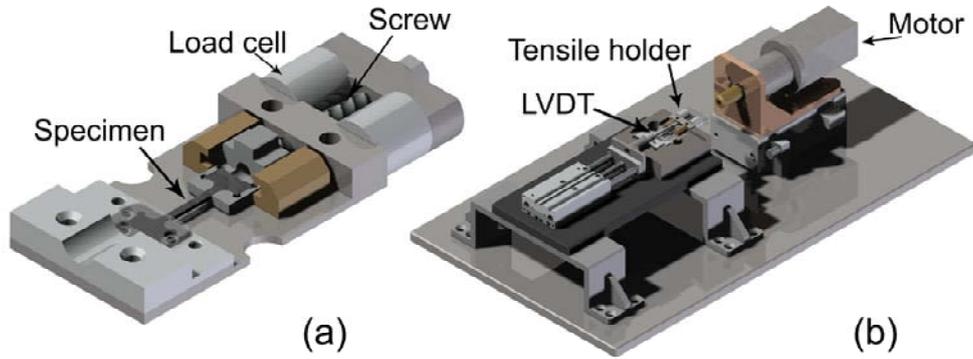


Figure 3. Tensile holder with microtensile specimen (a); fatigue testing machine (b).

### EXPERIMENTAL RESULTS AND COMMENTS

Focusing the results obtained applying lower stress values ( $\sigma_{\max} = 280$  MPa and  $\sigma_{\min} = 120$  MPa) the main observed damaging morphologies and their evolution with the fatigue loading are shown in Figs. 4-6.

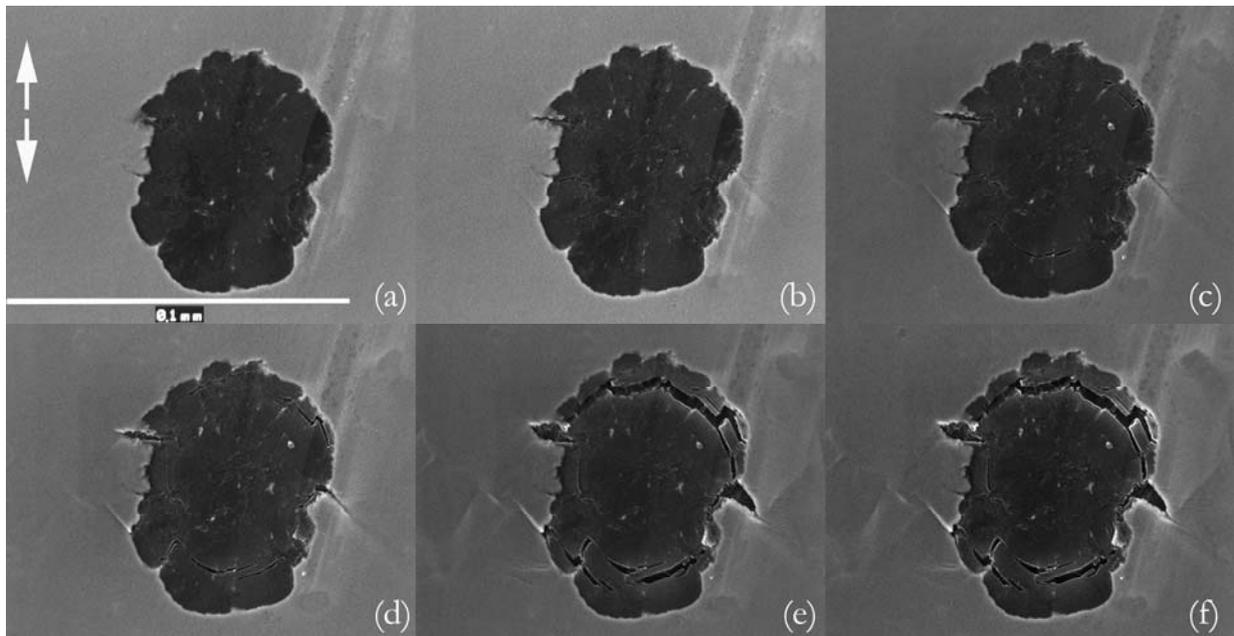


Figure 4: EN GJS350-22 DCI ( $\sigma_{\max} = 280$  MPa and  $\sigma_{\min} = 120$  MPa). SEM in situ surface analysis corresponding to the following loading cycles: (a) 1; (b) 14100; (c) 38300; (d) 40100; (e) 46000; (f) 48100 cycles (arrows show the loading direction).

After the first cycle, no damage is observed neither in ferritic matrix, nor in graphite nodules [Figs. 4-6, a). Furthermore, debonding of graphite nodule – ferritic matrix interface is not observed. This results agree with the results obtained in former experimental activities [8 – 12]: no damaging micromechanisms were activated in the elastic stage. After more than 14000 load cycles, damage initiates both at graphite nodules – ferritic matrix interface (mainly slip bands emission) and in graphite elements (Figs. 4 - 6, b). Focusing graphite nodules, the main damaging micromechanism is a sort of debonding of the graphite core obtained during solidification (both directly from the melt and during eutectic solidification) with respect to the graphite shell obtained during cooling, due to C solubility decrease in austenite grains. Microcracks in the nodule center are only seldom observed.

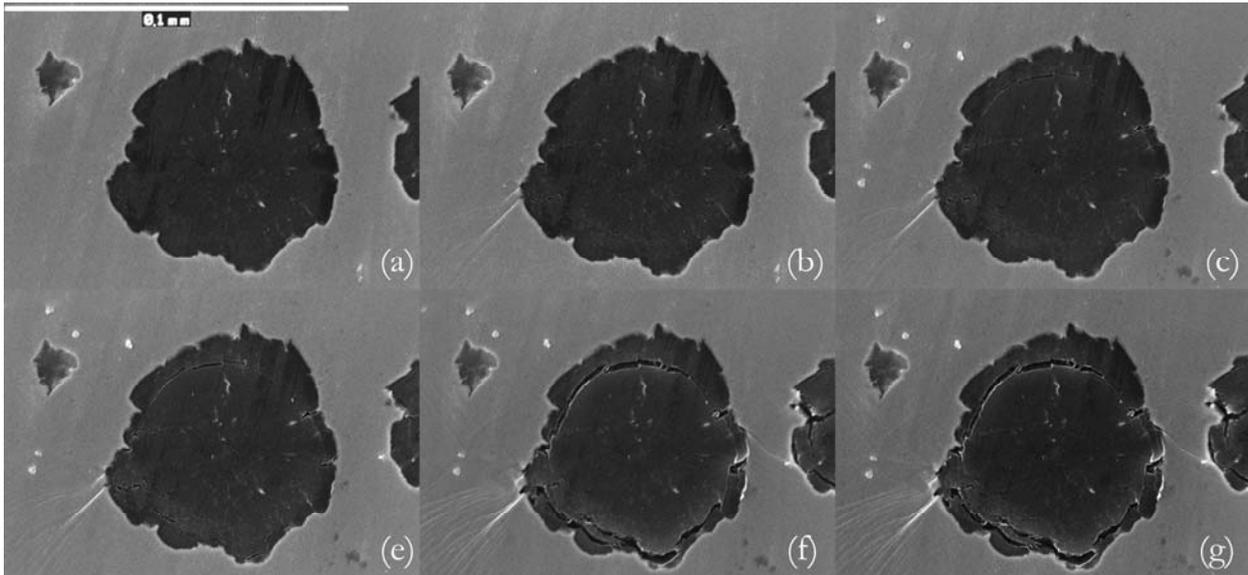


Figure 5. EN GJS350-22 DCI. SEM in situ surface analysis corresponding to the same loading conditions of Fig. 4.

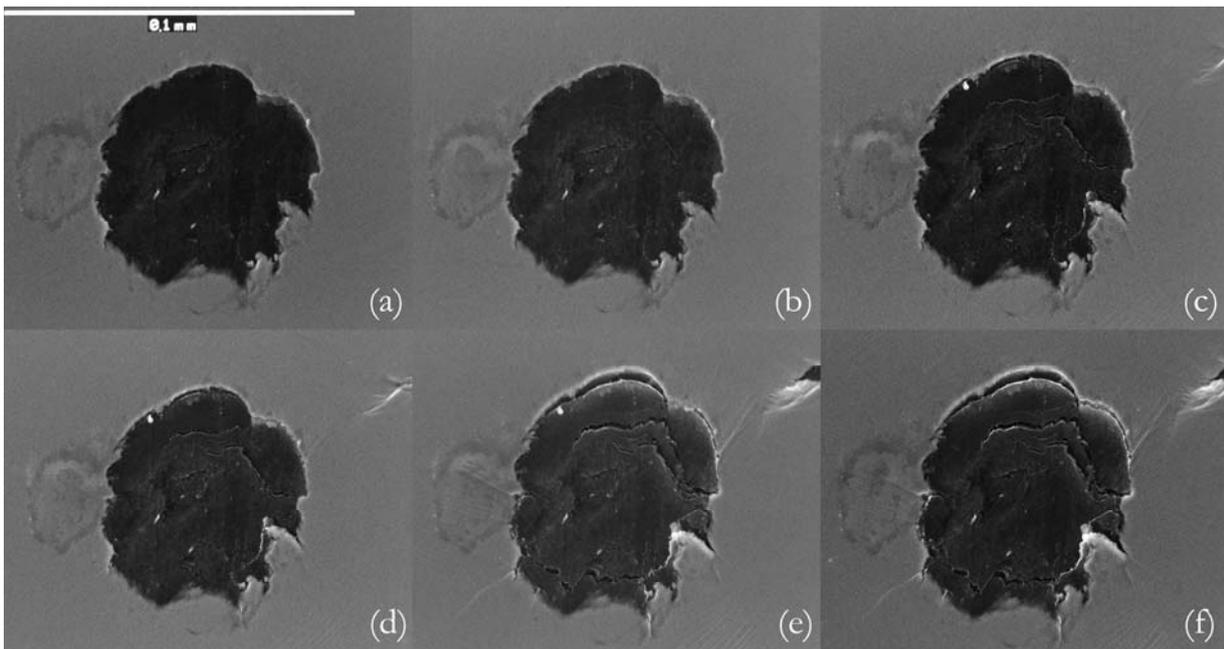


Figure 6. EN GJS350-22 DCI. SEM in situ surface analysis corresponding to the same loading conditions of Fig. 4.

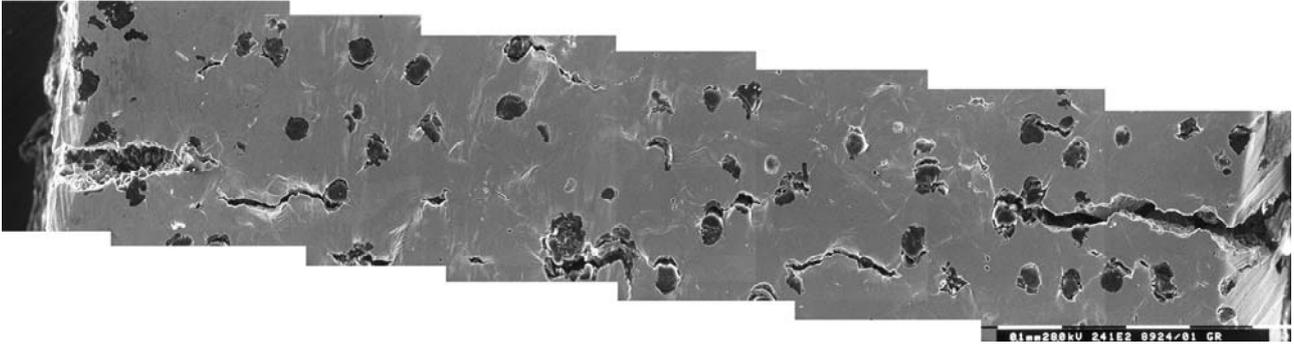


Figure 7. EN GJS350-22 DCI. SEM in situ surface analysis (48100 cycles; 5 cycles before the final rupture).

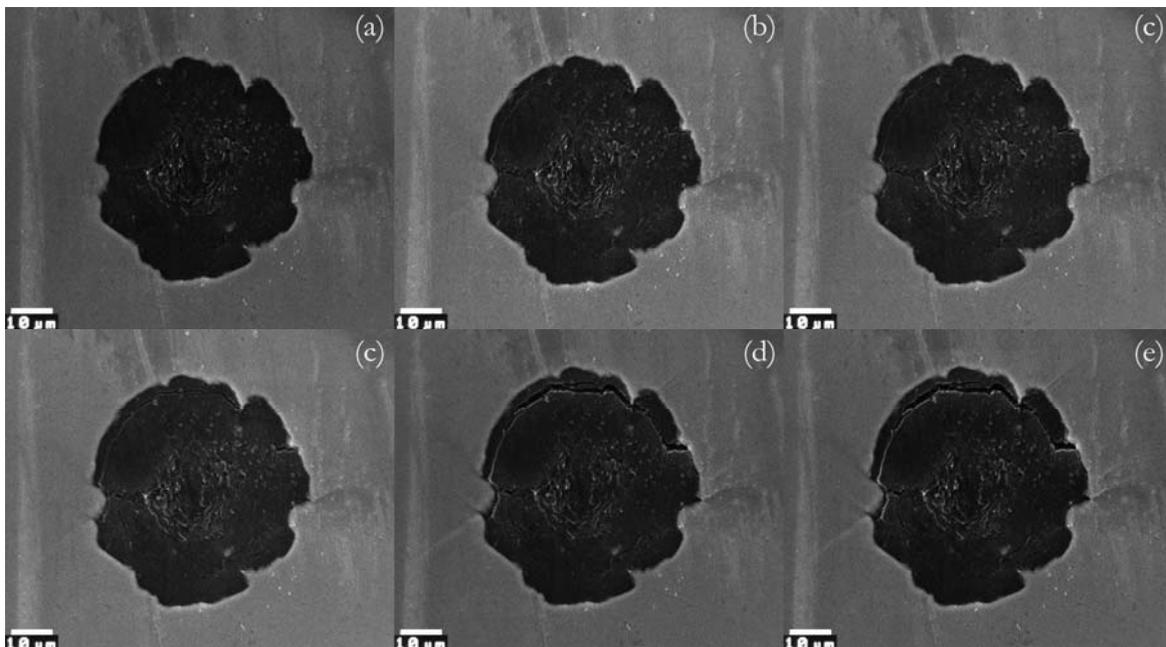


Figure 8. EN GJS350-22 DCI ( $\sigma_{\max} = 320$  MPa and  $\sigma_{\min} = 120$  MPa). SEM in situ surface analysis corresponding to the following loading cycles: (a) 1; (b) 20; (c) 40; (d) 180; (e) 380; (f) 680 cycles.

Focusing ferritic matrix, slip bands become more and more evident with the increase of fatigue cycles number (Figs. 4-6, b-f) and microcracks initiate corresponding to the interface matrix-nodule (e.g., Figs. 4 c-f) and propagate in ferritic matrix.

A few cycles before the specimen final rupture (Fig. 7), it is possible to observe that matrix damaging is characterized by the presence of many microcracks that are homogeneously distributed, with all the graphite nodules that are highly damaged, according to the micromechanisms described in Figs. 4-6.

Considering the tests performed applying a higher  $\sigma_{\max}$  ( $\sigma_{\max} = 320$  MPa and  $\sigma_{\min} = 120$  MPa), the main observed damaging morphologies and their evolution with the fatigue loading are shown in Figs. 8-9. Also for this testing condition, no damage is observed after 1 cycle.

Focusing graphite nodule elements, different damaging morphologies were observed, already after 20 cycles:

- Cracks initiate and propagate at the interface between the shell obtained from the reduced Carbon solubility in  $\gamma$  phase, and the nucleus directly obtained from the melt [12, 13], Figs. 8 – 10: it is

possible to observe a sort of “onion-like” mechanism implying a debonding of the graphite nodule core obtained directly from the melt with respect to the outer graphite shell obtained from the negligible carbon solubility in ferrite.

- Cracks initiate in the nodule central area and propagate orthogonally to the loading direction (Fig. 9);

- Graphite nodules – ferritic matrix debonding is only seldom observed.

The increase of fatigue cycles number implies both an evolution of the already initiated damaging mechanisms, with opening and propagation cracks, and the initiation of new damaged points.

Focusing the ferritic matrix, the main damaging mechanisms are:

- emanation of slip lines usually corresponds to the nodule equator, already after 20 cycles; the cycles number increase implies the emanation of new slip lines;

- nucleation and propagation short cracks corresponding to the graphite nodules – ferritic matrix interfaces (e.g. Fig. 10).

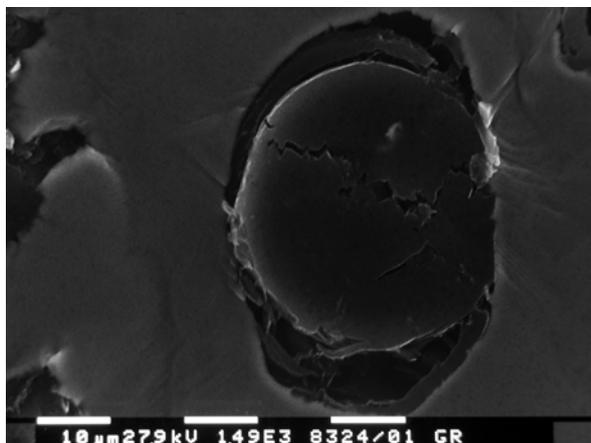


Figure 9. EN GJS350-22 DCI. SEM in situ surface analysis corresponding to the same loading conditions of Fig. 8.

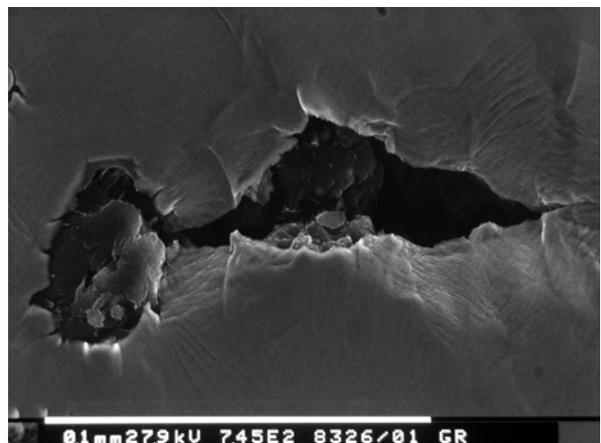


Figure 10. EN GJS350-22 DCI. SEM in situ surface analysis corresponding to the same loading conditions of Fig. 8.

## CONCLUSIONS

In this work, fatigue damaging micromechanisms in a ferritic DCI were investigated by means of uniaxial fatigue tests, considering two different loading conditions, with different  $\sigma_{\max}$  values (320 and 280 MPa respectively;  $\sigma_{\min}$  is 120 MPa for the two investigated loading conditions). Step by step fatigue tests were performed on microtensile specimens and lateral surfaces were observed by means of a scanning electron microscope (SEM).

On the basis of the experimental results, damaging micromechanisms could be summarized as follows:

### Ferritic matrix.

Damaging micromechanisms seems to be the same for the two investigated loading conditions:

- slip lines emanation usually corresponding to nodules equator;
- nucleation and propagation of short cracks corresponding to the graphite nodules – ferritic matrix interfaces: final rupture is due to the linkage of these microcracks.

### Graphite nodules.

Although the investigated nodules number is quite significant for the two investigated loading conditions, results described in the following lines should be confirmed by further experimental analysis.

Considering higher  $\sigma_{\max}$  (320 MPa):

- both graphite nodules – ferritic matrix debonding and cracks initiation and propagation at the interface between the graphite core obtained directly from the melt and the graphite inner shell obtained during eutectic solidification are only seldom observed.
- microcracks initiate and propagate at the interface between the shell obtained from the reduced Carbon solubility in  $\gamma$  phase and the nucleus directly obtained from the melt (onion-like mechanism);
- microcracks can also initiate in the nodule central area and propagate orthogonally to the loading direction.

Considering lower  $\sigma_{\max}$  (280 MPa):

- graphite nodules – ferritic matrix debonding is only seldom observed.
- a sort of debonding of the graphite core obtained during solidification (both directly from the melt and during eutectic solidification) with respect to the graphite shell obtained during cooling due to C solubility decrease in austenite grains, developing a sort of “onion-like” mechanism.
- Microcracks initiation and propagation in the nodule center is only seldom observed.

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