Fatigue damaging micromechanisms in a ferritic ductile cast iron

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ABSTRACT. Fatigue damaging micromechanisms in a ferritic ductile cast iron were investigated by using a scanning electron microscope (SEM) with a microtensile holder. Fatigue tests were performed under load control conditions and damage analysis were performed according to a step by step experimental procedure: specimens surfaces were observed by means of a SEM during the test ("in situ" tests). Experimental results show the complex role played by the graphite nodules.

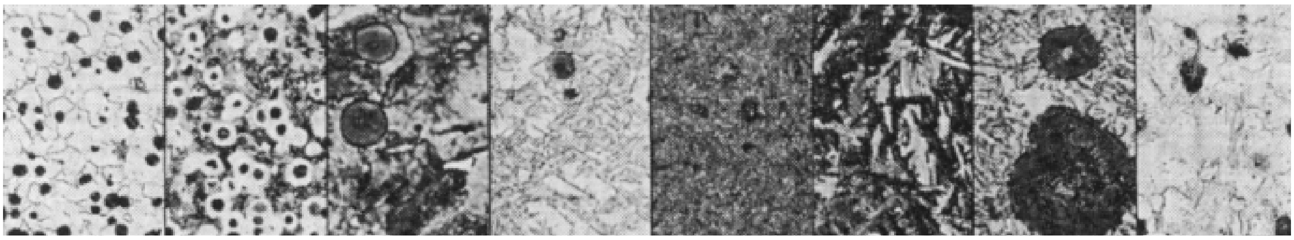
SOMMARIO. Sono stati analizzati i micromeccanismi di danneggiamento a fatica in una ghisa sferoidale a matrice ferritica utilizzando un microscopio elettronico a scansione (SEM) equipaggiato con un sistema di afferraggio miniaturizzato. Le prove di fatica sono state effettuate in condizioni di controllo della sollecitazione e l'analisi del danneggiamento è stata effettuata interrompendo l'esecuzione della prova, mantenendo il provino sollecitato per un valore pari al carico massimo. I risultati ottenuti hanno permesso di evidenziare il complesso ruolo svolto dai noduli di grafite.

KEYWORDS. Fatigue; Ferritic ductile iron; Damaging micromechanism.

INTRODUCTION

Ductile cast irons (DCIs) are characterized by a very interesting combination of overall properties: high ductility (up to more than 18%), high strength (up to 850 MPa and, considering austempered ductile iron, up to 1600 MPa) and good wear resistance. They are widely used in a number of applications, e.g. wheels, gears, crankshafts in cars and trucks etc.
Matrix controls these good mechanical properties [1, 2] and matrix names are commonly used to designate spheroidal cast iron types (Fig. 1):
- ferritic DCIs are characterized by good ductility, with tensile strength values that are equivalent to low carbon steel.
- pearlitic DCIs show high strength values, good wear resistance and moderate ductility.
- ferritic-pearlitic grades properties are intermediate between ferritic and pearlitic ones.
- martensitic DCIs show very high strength, but low levels of toughness and ductility.
- bainitic grades are characterized by high hardness.
- austenitic DCIs show good corrosion resistance, good strength and dimensional stability at high temperature.
- austempered grades show a very high wear resistance and fatigue strength.

Microstructure influence on tensile test results is shown in Fig. 2.



Ferritic	Ferritic-pearlitic	Pearlitic	Martensitic	Tempered martensitic	ADI Grade 150	ADI Grade 230	Austenitic
414 MPa	552 MPa	690 MPa	N.A.	793 MPa	1050 MPa	1600 MPa	310 MPa

Figure 1: DCIs different microstructures (with UTS values; magnifications are different) [2].

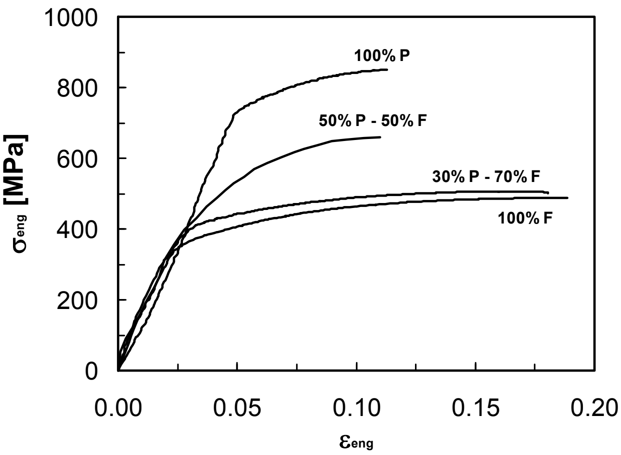


Figure 2: Ductile cast iron microstructure influence on tensile tests results.

Focusing fatigue crack propagation resistance, references results show an evident influence of matrix microstructure, graphite elements morphology, size and volume fraction and loading conditions [3-18], Figs. 3 and 4.

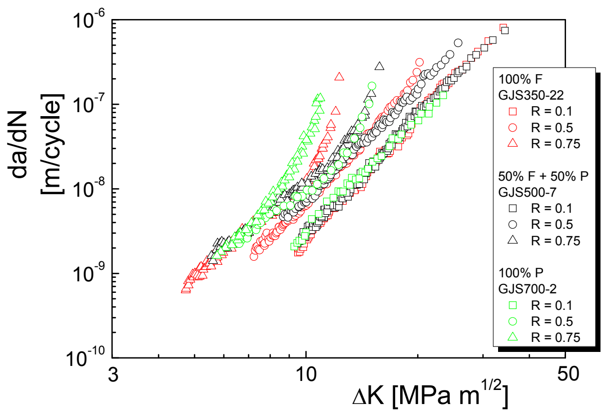


Figure 3: Stress ratio and microstructure influence on fatigue crack propagation resistance of ferritic-pearlitic DCI (obtained controlling the chemical composition).

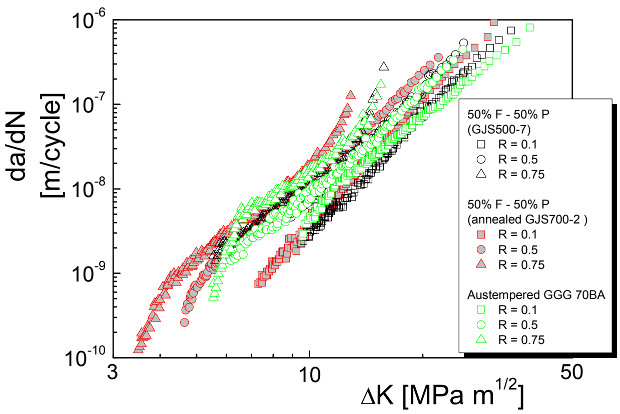


Figure 4: DCI fatigue crack propagation resistance in ferritic-pearlitic and austempered DCIs.

Considering the fatigue crack propagation, graphite elements do not only act as "crack arresters", due to their peculiar shape, but, depending on matrix microstructure, they can also increase the DCI fatigue crack propagation resistance by means of an increase of the crack closure effect, with a consequent decrease of the ΔK value that is effective at the crack tip.

Graphite nodules "ductile" or "fragile" debonding seems to be one of the main damaging micromechanism, with a respectively more or less evident plastic deformations of the matrix around the nodules. A model of the interaction between fatigue crack and graphite nodules during debonding, for different applied K values, is shown in Fig. 5.

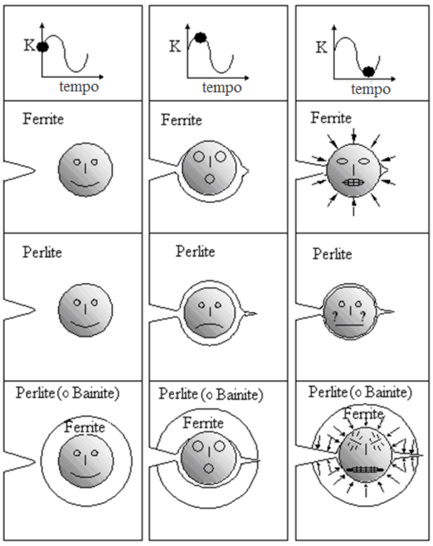


Figure 5: Microstructure influence on graphite nodules – matrix debonding.

Ferritic DCI, implying an evident graphite nodules plastic debonding with an evident matrix plastic deformation. Corresponding to higher K values, a matrix plastic deformation is obtained and, corresponding to the lower K values, the "mechanical obstruction" is more important, implying a partial graphite nodule disgregation.
Considering pearlitic DCI, fragile debonding implies a negligible matrix plastic deformation: as a consequence, graphite nodule merely play as "mechanical obstruction", with a lower crack closure effect corresponding to K_{min}. Comparing the fatigue crack propagation resistance of the investigated ferritic and pearlitic DCIs, the consequence is evident: higher R and ΔK values implies an increase of the importance of the ductile debonding in ferritic DCI, with a consequent increase of the crack closure effect importance and, consequentely, obtaining lower crack growth rate values for the same loading conditions.
Ferritic-pearlitic GJS500-7 and austempered DCIs are characterized by an analogous phases distribution, with a pearlitic or bainitic matrix, and ferrite grains as shields around graphite nodules (more evident for the GJS500-7). Considering that both pearlite and bainite are characterized by lower ductility values if compared to ferrite, an additional crack closure effect mechanism has been proposed. This mechanism is connected to the peculiar phases distribution and to their different mechanical behaviour. During fatigue loading, with K that ranges between K_{max} and K_{min}, deformation level in the involved phases (ferrite and pearlite or bainite) is quite different:

- Corresponding to K_{max}, due to the higher ferrite ductility, plastic deformation level in ferritic shields is higher than in pearlitic or bainitic matrix;
- Nearby K_{min} values, pearlitic (or bainitic) matrix induces a compression stress state on ferritic shields and, consequently, on graphite nodules, with a consequent increase of crack closure effect importance. Both GJS500-7 and austempered DCI show the higher fatigue crack propagation resistance, mainly corresponding to higher R and ΔK values.

The aim of this work has been the analysis of the damaging micromechanism corresponding to oligocyclic fatigue conditions. A ferritic DCI has been investigated by means of step by step fatigue tests were performed considering microtensile specimens: surfaces were observed by means of a scanning electron microscope (SEM) during fatigue tests.

MATERIAL AND EXPERIMENTAL PROCEDURE

A fully ferritic DCI was considered (chemical compositions is in Tab. 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. Three fatigue

tests were performed under load control conditions (σ_{max} = 320 MPa ; σ_{min} = 120 MPa), with a loading frequency of 0.03 Hz. 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 test, 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 (tensile holder and the fatigue testing machine are shown in Figs 6a and 6b, respectively).
In order to perform SEM observations, fatigue loading was stopped after 1, 20, 40, 60, 80 cycles. Hereafter, observations were performed every 100 cycles.

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

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

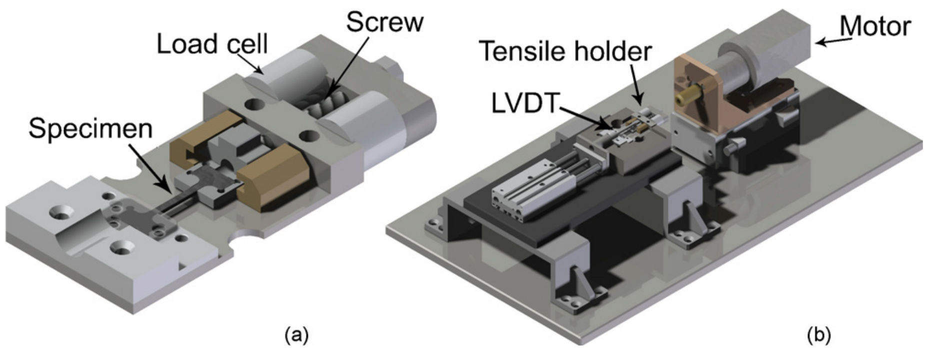


Figure 6: Tensile holder with microtensile specimen (a); fatigue testing machine (b).

RESULTS AND DISCUSSION

SEM allowed to identify different damaging micromechanisms both in the matrix and corresponding to graphite nodules. Unfortunately, final rupture was always obtained far from the analysed zone (specimen central area). However, after the final rupture, specimens lateral surfaces near the fracture were also SEM observed. Final rupture were obtained after 672, 731 and 795 cycles.
Figs 7, 8 and 9 show the damage evolution corresponding to three different nodules (big white arrows in Fig. 7 shows the loading direction).
For all the investigated specimens, and all the observed nodules, no damage is observed after 1 cycle. Considering that the investigated loading conditions correspond to the ferritic DCI elastic stage (Fig. 2), this agrees with the damaging micromechanisms identified in ferritic DCI during "in situ" tensile tests [14-16].
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 γ phase, and the nucleus directly obtained from the melt [16, 19], Fig. 7 and 8 (after 20 cycles, white arrows): 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 (Figs. 7, 8 and 9, after 20 cycles; white arrows);
- Graphite nodules – ferritic matrix debonding is only seldom observed (Fig. 8, green arrows).
The increase of fatigue cycles number implies both an evolution of the already initiated damaging mechanisms, with opening and propagation cracks (Fig. 7, from 20 to 680 cycles, and Fig 8 corresponding to 380 cycles, respectively), and the initiation of new damaged points (Fig. 8, corresponding to 380 cycles; white arrows).
Focusing the ferritic matrix, the main damaging mechanisms are:
- emanation of slip lines usually corresponds to the nodule equator (orange arrows), already after 20 cycles; the cycles number increase implies the emanation of new slip lines (e.g., Fig 9 after 380 cycles);
- nucleation and propagation short cracks corresponding to the graphite nodules – ferritic matrix interfaces.

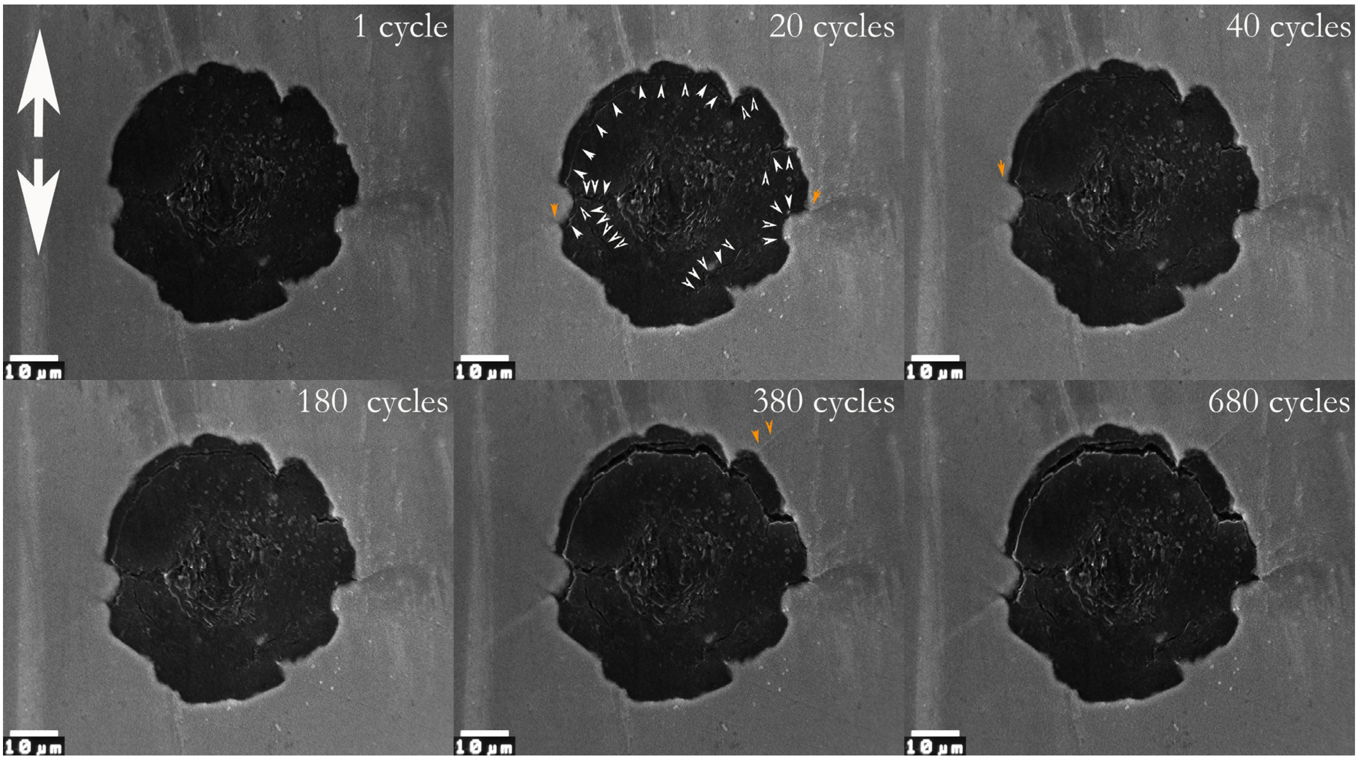


Figure 7: Ferritic DCI fatigue damage evolution (big white arrows show the loading direction).

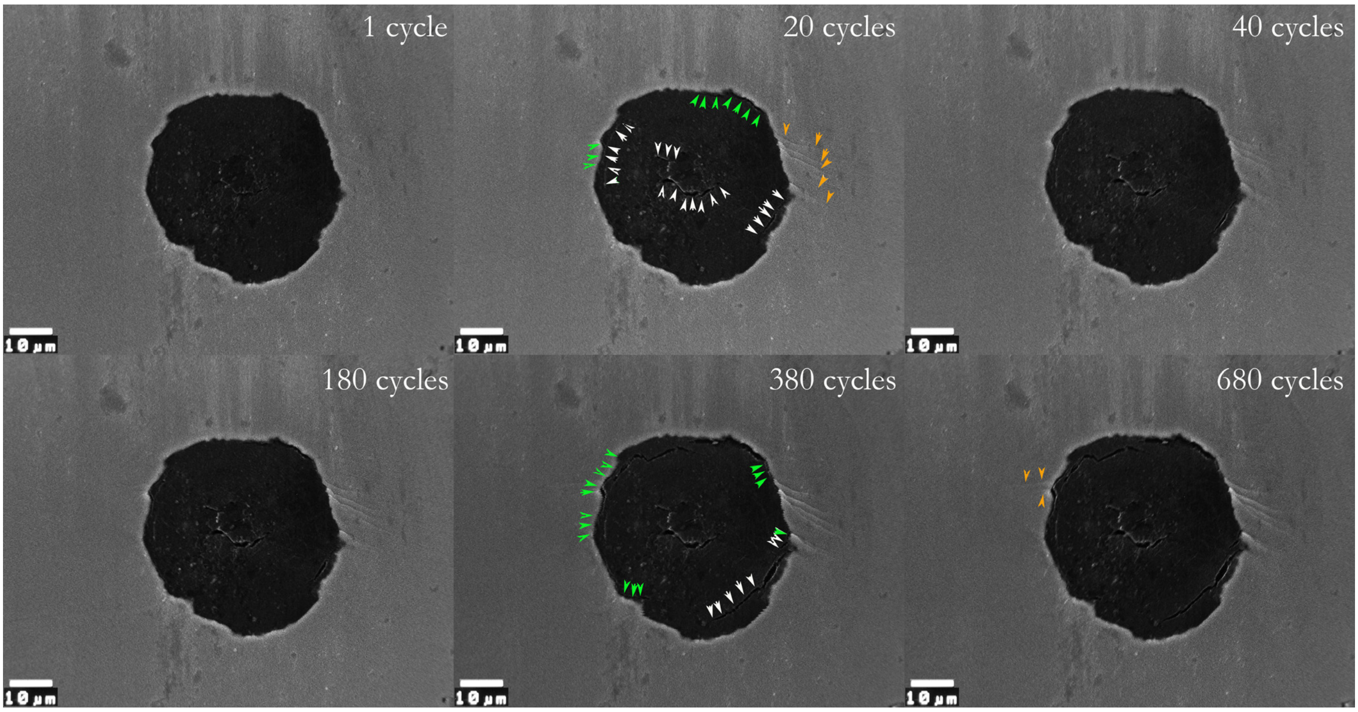


Figure 8: Ferritic DCI fatigue damage evolution.

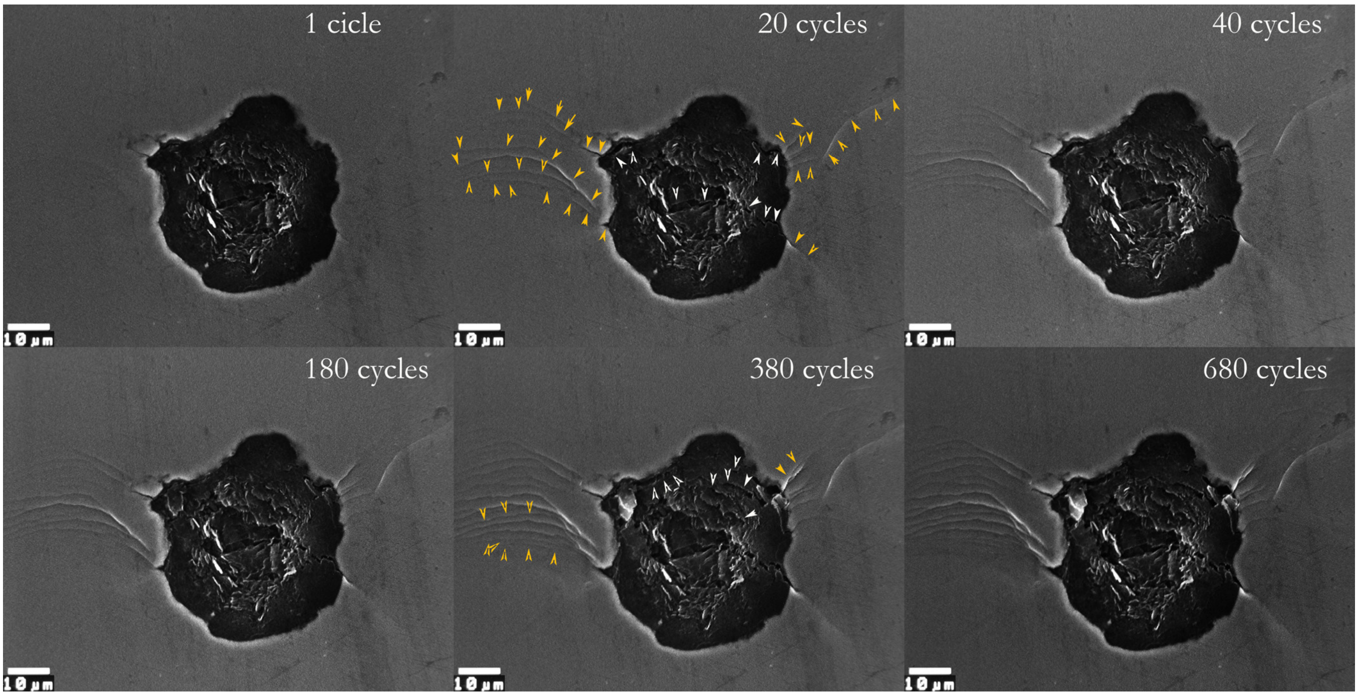


Figure 9: Ferritic DCI fatigue damage evolution.

Considering that SEM analysis was not performed near the final rupture surface, observed nodules allowed to analyse only the first damaging stages. As a consequence, final damaging micromechanisms were observed only after the final rupture, by means of a SEM analysis of the nodules near the fracture surface.

Focusing graphite nodules, both the "onion-like" mechanism and the crack initiation and propagation in the nodule nuclei are completely developed, with an evident ferrite plastic deformation (Fig. 10). Furthermore, another damaging mechanism is seldom observed (Fig. 11): cracks initiate and propagate at the interface between the graphite core obtained directly from the melt (C_M) and the graphite inner shell obtained during eutectic solidification (C atoms solid diffusion through austenite shells, C_E). This damaging morphology was not observed during the step by step experimental analysis.

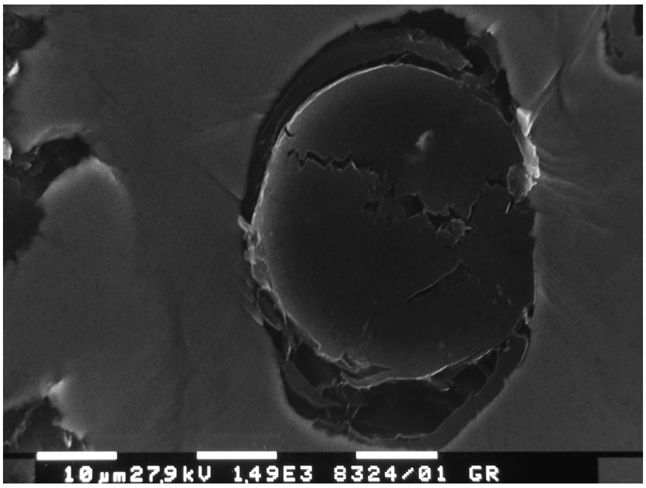


Figure 10: Ferritic DCI fatigue damage evolution (near fracture surface).

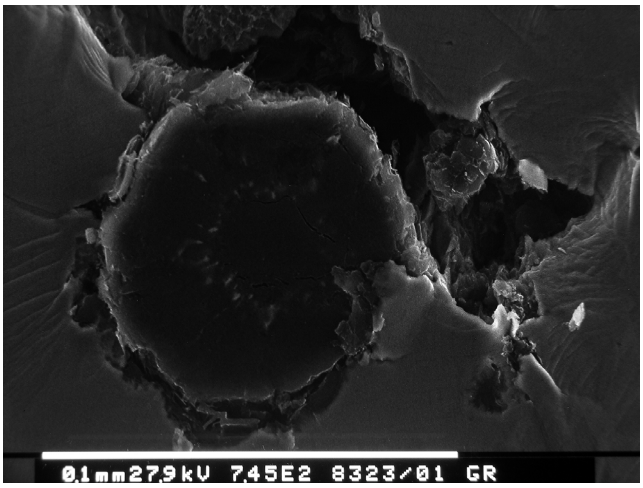


Figure 11: Ferritic DCI fatigue damage evolution (near fracture surface).

Focusing ferritic matrix, slip lines are really evident both on the lateral surface (Fig. 12) and on the fracture surface (Fig. 13). Final rupture is obtained due to the linkage of cracked graphite nodules by microcracks (Fig. 12).

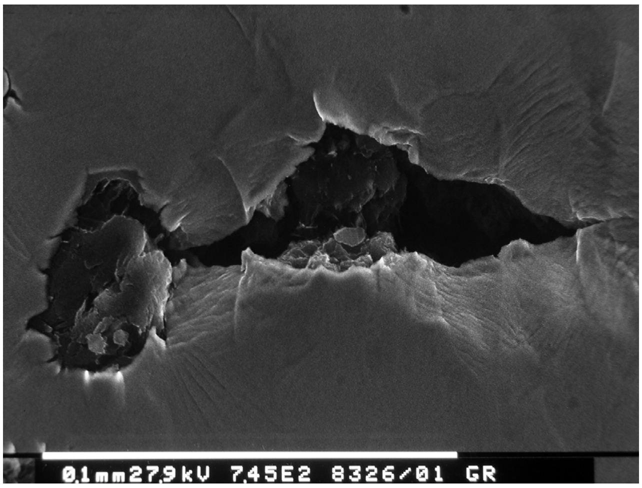


Figure 12: Ferritic DCI fatigue damage evolution (near fracture surface).

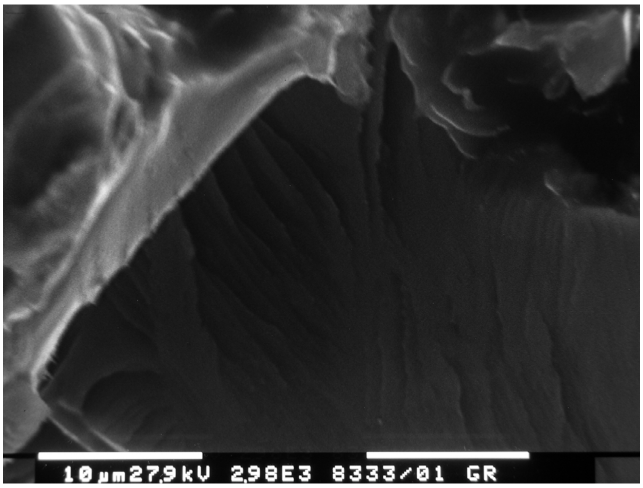


Figure 13: Ferritic DCI fracture surface.

CONCLUSIONS

Ferritic DCIs are characterized by good ductility, with tensile strength values that are equivalent to a low carbon steel. Their fatigue crack propagation resistance is affected by the graphite nodules presence (density, shape, distribution), by the matrix microstructure and by loading conditions. In this work, fatigue damaging micromechanisms in a ferritic DCI were investigated by means of uniaxial fatigue tests. 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:

Graphite nodules.

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

Ferritic matrix.

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

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