Pearlitic ductile cast iron: damaging micromechanisms at crack tip

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ABSTRACT. Ductile cast irons (DCIs) are characterized by a wide range of mechanical properties, mainly depending on microstructural factors, as matrix microstructure (characterized by phases volume fraction, grains size and grain distribution), graphite nodules (characterized by size, shape, density and distribution) and defects presence (e.g., porosity, inclusions, etc.). Versatility and higher performances at lower cost if compared to steels with analogous performances are the main DCIs advantages.
In the last years, the role played by graphite nodules was deeply investigated by means of tensile and fatigue tests, performing scanning electron microscope (SEM) observations of specimens lateral surfaces during the tests ("in situ" tests) and identifying different damaging micromechanisms.
In this work, a pearlitic DCIs fatigue resistance is investigated considering both fatigue crack propagation (by means of Compact Type specimens and according to ASTM E399 standard) and overload effects, focusing the interaction between the crack and the investigated DCI microstructure (pearlitic matrix and graphite nodules). On the basis of experimental results, and considering loading conditions and damaging micromechanisms, the applicability of ASTM E399 standard on the characterization of fatigue crack propagation resistance in ferritic DCIs is critically analyzed, mainly focusing the stress intensity factor amplitude role.

KEYWORDS. Ductile cast irons (DCIs); Fatigue crack propagation; Graphite nodules; Damaging micromechanisms.

INTRODUCTION

Ductile cast irons (DCIs) have been relatively recently developed and they are characterized by the presence of free graphite with a nodule shape (instead of lamellae as in grey cast iron): this allows to combine the more peculiar cast iron property (castability) with mechanical properties that are similar to those of carbon steels [1] (first of all, toughness). DCIs are 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 critical applications as containers for storage and transportation of nuclear wastes [1-2]. Matrix controls mechanical properties and matrix names are used to designate spheroidal cast iron types. Many different DCIs grades are commercially available. Among them, ferritic-pearlitic DCIs offer a wide range of mechanical properties, with ferritic grades that are characterized by good ductility and a tensile strength (more or less equivalent to a low carbon steel), pearlitic DCIs that show higher strength values, good wear resistance and moderate ductility and, finally, ferritic–pearlitic grades properties that are intermediate between ferritic and pearlitic ones, at least considering tensile strength (Fig. 1). In fact, considering the fatigue crack propagation resistance (Fig. 2), the ferritic-pearlitic DCI seems to be characterized by the best behaviour, at least for higher ΔK and R values.

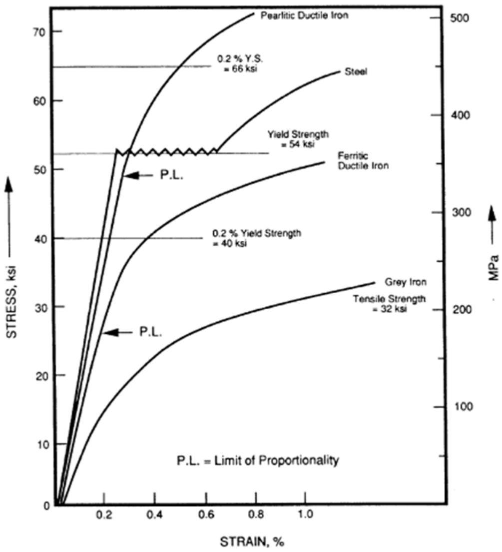


Figure 1: Stress –strain behaviour for carbon steel, grey iron and ferritic and pearlitic DCIs [1].

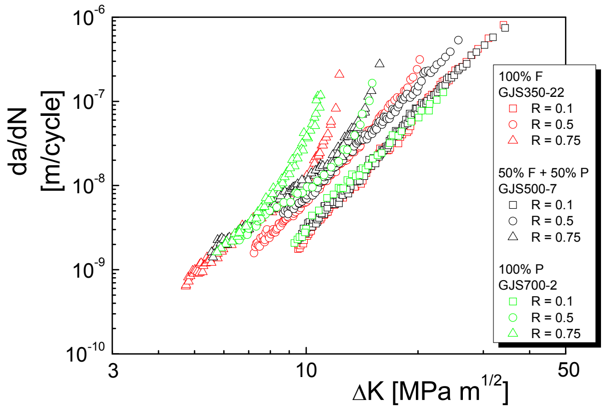


Figure 2: Ferritic-pearlitic DCIs. Microstructure and stress ratio influence on fatigue crack propagation [8].

Considering the fatigue resistance, and considering both the initiation and propagation of micro- and macro- cracks, the role played by graphite nodules is not univocally determined. Different mechanisms are proposed for the graphite nodules [3-7]:
- "rigid spheres" not bonded to the matrix and acting like voids under tension;
- "crack-arresters", due to their peculiar shape that minimizes the stress intensification at the crack tip;
- "crack closure effect raisers", due to the role they play at the lower values of the applied K_{min}.

Other research activities allowed to conclude that graphite nodule cannot be regarded as voids with no strength and that they don't cause micro-notch stress concentration by itself [8]. It has been proposed [9]that the role played by the graphite nodules in DCIs fatigue crack propagation is more complex, suggesting the presence of a mechanical properties gradient inside the graphite nodules, probably due to the different graphite nodules solidification and growth mechanisms.

Considering the fracture mechanics principles, stress intensity factor ("K") is used to quantify the stress state ("stress intensity") near the crack tip caused by a remote load or residual stresses and, considering fatigue crack propagation, stress intensity factor amplitude (e.g. $\Delta K = K_{max}-K_{min}$) is the main parameter used to characterize the stress conditions at the crack tip. Both K and ΔK usefulness is confirmed only considering an homogeneous and linear-elastic body: obviously, a crack tip plastic zone is always present, but, if its radius is negligible, the K parameter is still valid. Under monotonic loading, plastic zone size is usually estimated as follows:

$$r_y = \frac{1}{2\pi}\left(\frac{K}{\sigma_y}\right)^2 \quad \text{(plane stress conditions)} \qquad (1)$$

$$r_y = \frac{1}{6\pi}\left(\frac{K}{\sigma_y}\right)^2 \quad \text{(plane strain conditions)} \qquad (2)$$

Considering a fatigue crack propagation problem, Eqs. (1) and (2) represent the crack tip plastic zone corresponding to the upward excursion of the load cycle (up to $K(t) = K_{max}$). Fatigue crack propagation is characterized by the presence of a "reversed" or "cyclic" plastic zone, r_{rpz} (four times lower than the monotonic value corresponding to K_{max}): the tensile load reduction from the σ_{max}, and the presence of the surrounding elastic body, imply a compression condition at the crack tip. Considering that, for R = 0.1, applied ΔK value ranges between 9 and 32 MPa√m (Fig. 2), assuming the investigated pearlitic DCI as an homogeneous material, and according to relationships (1) and (2), crack tip plastic zone ($r_{pzK_{max}}$, for $K = K_{max}$) and reversed plastic zone radii range respectively:

Crack tip plastic zone radius, $r_{pzK_{max}}$:
- between 0.099 and 1.258 mm (plane stress conditions);
- between 0.033 and 0.419 mm (plane strain conditions).

Reversed plastic zone radius, r_{rpz}:
- between 0.024 and 0.314 mm (plane stress conditions);
- between 0.008 and 0.105 mm (plane strain conditions).

Considering that the maximum values of the graphite nodules diameters (about 40-50 μm), it is evident that, for lower ΔK and R values, a pearlitic DCI cannot be considered as an homogeneous material, with graphite nodules diameters that are comparable to the main fracture mechanics geometrical parameters (first of all, the reversed plastic zone radius). Does this inhomogeneity have consequences on the crack propagation paths? The aim of this work is focused on the analysis of the influence of graphite nodules on damaging micromechanisms and on crack path, considering both cyclic loading and overloads and considering the role played by the pearlitic matrix.

INVESTIGATED MATERIAL AND EXPERIMENTAL PROCEDURE

In this work a pearlitic DCI (EN GJS700-2) was considered. Investigated DCI chemical composition is shown in Tab. 1: it is characterized by an almost fully pearlitic microstructure and by a high graphite elements nodularity (higher than 85%).

C	Si	Mn	S	P	Cu	Mo	Ni	Cr	Mg	Sn
3.59	2.65	0.19	0.012	0.028	0.04	0.004	0.029	0.061	0.060	0.098

Table 1: DCI EN GJS700-2 chemical composition (95% pearlite, 5% ferrite).

In order to analyze the damage evolution during fatigue crack propagation, or after overloads, 10 mm thick CT (Compact Type) specimens lateral surfaces were previously metallographically prepared. Long fatigue cracks (18-19 mm) with negligible crack tip plastic zones, were obtained performing two or three times the force shedding procedure described in ASTM E647 [10], with the applied ΔK value that follows the relationship:

$$\Delta K = \Delta K_0 e^{\left[C(a-a_0)\right]} \qquad (3)$$

The decrease of the applied ΔK value implies a decrease of the crack growth rate and of the crack tip plastic zone radious: when a very low crack growth rate value was obtained (about 10^{-10} m/cycle), the ΔK_0 value was increased, allowing to the fatigue crack to propagate again up to the final crack length (18-19 mm). Tests were performed using a computer controlled servohydraulic machine in constant stress ratio conditions ($R=P_{min}/P_{max}$ = 0.1), considering a 20 Hz loading frequency, a sinusoidal loading waveform and laboratory conditions. Crack length measurements were performed by means of a compliance method using a double cantilever mouth gage and controlled using an optical microscope (x40). At the end of this procedure, a long fatigue crack was obtained, with a negligible crack tip plastic zone.

Subsequently, static overloads were applied in order to generate crack tip plastic zones: after each applied overload, Scanning Electron Microscope (SEM) and Digital Microscope (DM) specimens lateral surface observations were performed, considering both the crack path and the crack tip zone, investigating the damaging micromechanisms. SEM observations were mainly focused on the graphite nodules damaging analysis, while DM allowed a more complete analysis of the damage evolution in the pearlitic matrix (e.g., by means of the observation of slip lines evolution, less evident if observed by means of a SEM).

EXPERIMENTAL RESULTS AND COMMENTS

Fatigue crack propagation damaging micromechanisms

According to the SEM observations performed on Nital 2 etched specimens, fatigue crack propagation in pearlitic DCI is strongly influenced by the microstructure.

Focusing the pearlitic microstructure, fatigue crack can propagate both along the ferritic lamellae with a sort of delamination (usually, when pearlitic lamellae orientation is more or less parallel to crack propagation direction), and with a transgranular mechanism (preferentially, when pearlitic lamellae orientation is more or less orthogonal to crack propagation direction), respectively Fig. 3 and 4 (crack propagates from left to right). It is worth to note that both propagation micromechanisms seem to be discontinuous: according to the observed lateral surfaces, ferritic lamellae seems to be the first to fracture while cementite ones are the last to be broken, playing a ligament role. These fracture themselves when fatigue crack macroscopically propagates. A SEM failure analysis performed on the crack surface allows to observe:

- a "pseudo-cleavage" propagation mechanism, corresponding to the pearlite delamination;
- the presence of "pseudo-striations" that are not connected to the macroscopic crack growth rate, but, better, to the pearlite lamellae spacing, corresponding to the transgranular mechanism.

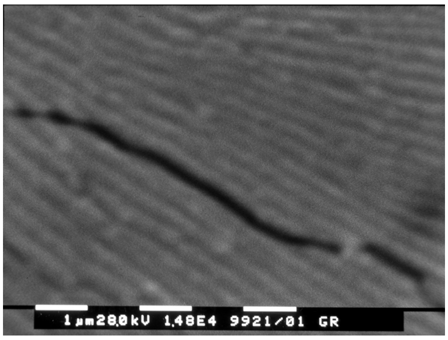


Figure 3: Fatigue crack propagation. Pearlite "delamination".

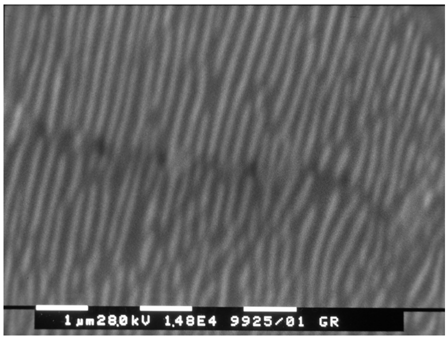


Figure 4: Fatigue crack propagation. Transgranular propagation.

Considering the interaction between fatigue crack and graphite nodules, two main damaging morphologies are observed with an analogous probability:

- debonding between the pearlitic matrix and the graphite nodules, sometimes with the initiation and propagation of a secondary crack in the nodule center, probably corresponding to the nodule nucleation site (Fig. 5);
- a sort of internal debonding between a "nodule core" and a "nodule shield" (Fig. 6), supposedly connected to the graphite nodules solidification and growth process (as observed more frequently in ferritic DCI [9]).

Furthermore, graphite nodules can also imply the crack bifurcation, as in Fig. 7. This is due to the crack tip stress field that induces a damage also in the nodules around the crack tip with different damaging morphologies, as in Fig. 8 and 9.

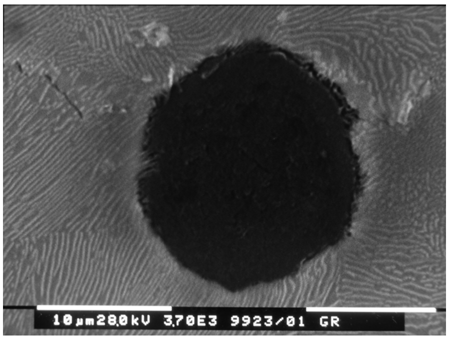


Figure 5: Pearlitic matrix-graphite nodule debonding (with secondary crack in the nodule center).

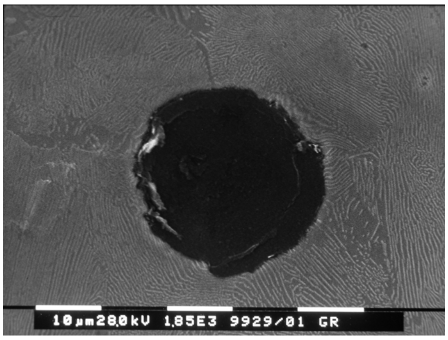


Figure 6: Graphite nodule internal debonding.

Figure 7: Crack bifurcation.

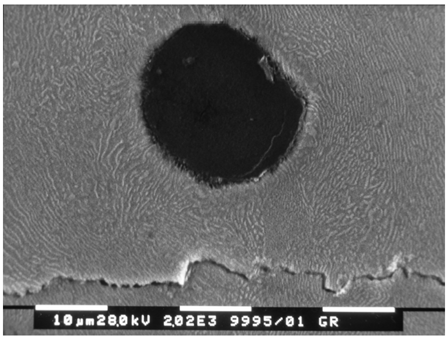


Figure 8: Damaged graphite nodule near the crack.

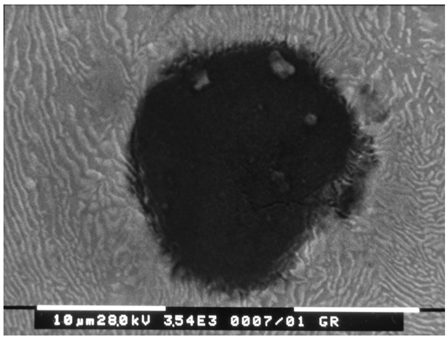
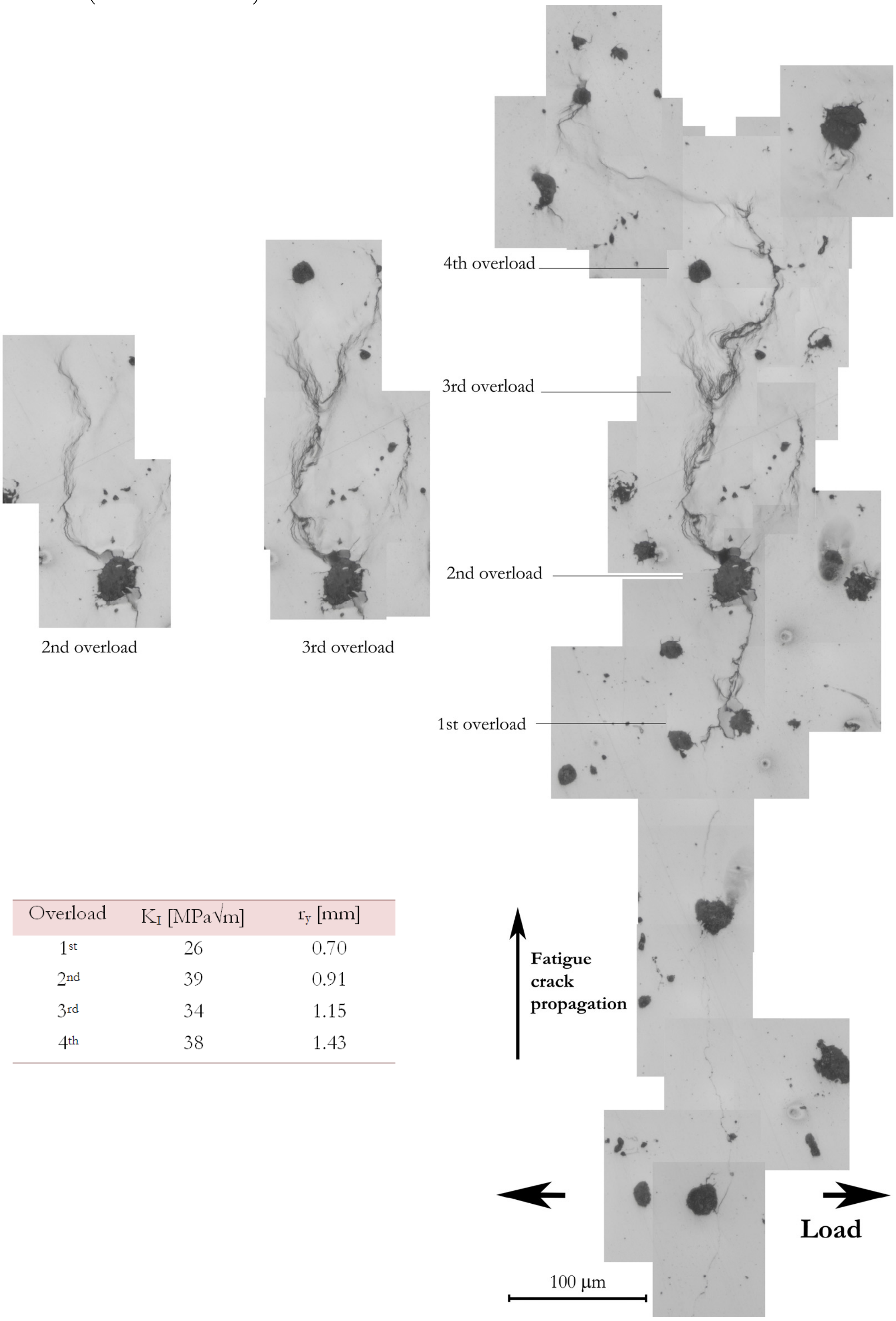


Figure 9: Damaged graphite nodule near the crack.

It is worth to note that damaged nodules are observed only near the crack tip. Considering Eq. 1 and 2, the zone containing the damaged nodules seems to be smaller than the crack tip plastic zone (more or less, the half).

Overloads effects

In Fig. 10 it is shown the effects of four different consecutive overloads on a fatigue crack obtained for threshold propagation conditions (DM observation).



Overload	K_I [MPa√m]	r_y [mm]
1st	26	0.70
2nd	39	0.91
3rd	34	1.15
4th	38	1.43

Figure 10: Crack profile. Fatigue stage + four different overloads (Digital Microscope observations).

The table in Fig. 10 shows the nominal K_I and r_y values, corresponding to the four applied and consecutive overloads. The first evident difference between the fatigue crack propagation stage and the effects of the overloads is the crack path profile (Fig. 10): fatigue crack propagation is characterized by a relatively smooth path. Instead, after every overload, the path is more and more tortuous and a sort of crack bifurcation is always observed, more and more evident with the increase of the applied load. Crack path is characterized by a large plasticization, with slip lines that become more and more evident with the increase of the applied load. Slip lines develop both around the crack path and at the crack tip. It is worth to note that slip lines density increase around the crack path with increase of the applied overload, also along the path (e.g., Fig. 10: from 2nd to 3rd overload). This is probably due to the different mechanical behaviour of ferrite and cementite lamellae and of graphite nodule that should imply a discontinuous DCI damage and crack propagation. When a higher overload is applied, the crack is only partially developed and a further plasticization is necessary to complete the crack propagation, anyway already visible by means of a DM with the lower overload previously applied.
Differences in damage level in graphite nodules are confirmed by means of SEM observation of the lateral surface of an etched specimen after a fatigue crack propagation and an overload (applied nominal K_I = 33 MPa$\sqrt{m}$; nominal r_y = 1.12 mm), Fig. 11.

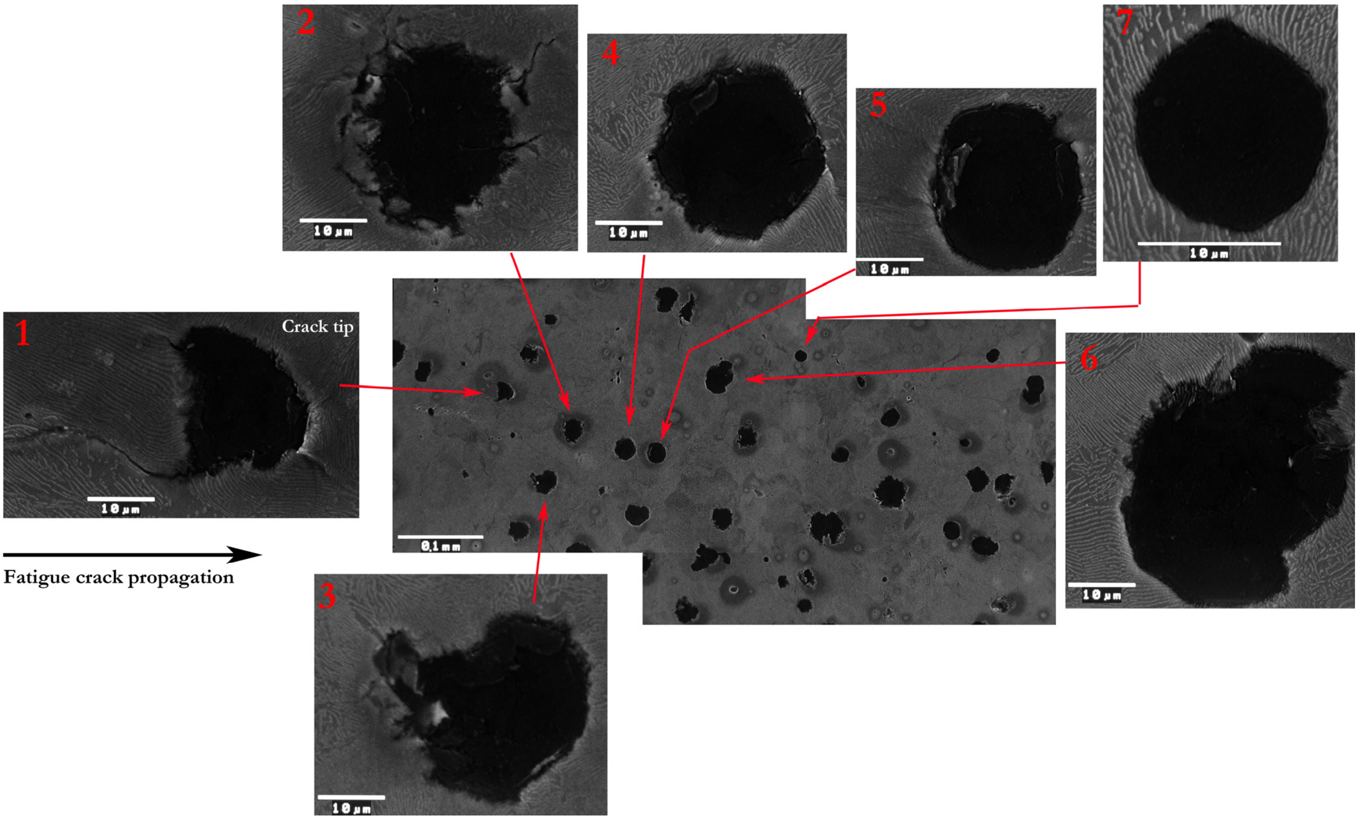


Figure 11: Crack profile. Fatigue stage + one overload (SEM observations).

Focusing graphite nodules, it is possible to observe different damaging micromechanisms, depending on the crack tip distance:
- near the crack tip (nodules 2-5) internal damage is evident, both as radial cracks (nodule 2) and as internal debonding between a nodule core and a nodule shield (analogously to the mechanism observed in Fig. 6 and 8 for the fatigue crack propagation stage);
- far from the crack tip (nodules 6 and 7), the debonding between the graphite nodules and the pearlitic matrix is the main damaging micromechanisms.

Considering the experimental results shown in Fig. 10 and 11, it is necessary to underline that the damaged zone does not correspond to the plastic zone calculated according to Eq. 1 and 2, both considering the fatigue crack propagation stage and considering the overloads. Crack tip stress field seems to be strongly influenced by the substantially composite nature of the investigated pearlitic DCI, implying a stress redistribution with a damage level gradient (obviously, higher near the crack tip) and a discontinuous crack propagation micromechanisms, also considering static overloads. As a consequence, stress intensity factor K_I does not seem the correct parameter to describe the stress state around the crack tip and it can be used only as a first approximation.

CONCLUSIONS

In this work damaging micromechanisms in a pearlitic DCI have been investigated, considering both the fatigue crack propagation and the overloads effects, focusing the attention both on the pearlic matrix (by means of Digital Microscope observations, mainly) and on the graphite nodules (by means of SEM observations, mainly). According to the experimental results the following conclusions can be summarized:

- focusing the pearlitic matrix, crack propagation is a discontinuous process, both considering the fatigue crack propagation process and considering the overloads effects;
- focusing the graphite nodules, different damaging micromechansims have been identified, mainly dependent on the distance from the crack tip; also the direct interaction between the crack and the graphite nodules has been analyzed, identifying two main damaging micromechanism;
- considering the composite nature of DCIs, the presence of a damage zone instead of a plastic zone around the crack tip, and the discontinuous crack propagation process, stress intensity factor K_I does not seem to be able to correctly describe the stress state near the crack tip in pearlitic DCIs.

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