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Fatigue crack propagation in a ferritic-pearlitic DCI: overload effects on damaging mechanisms

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Abstract

Ductile iron discovery in 1948 renewed the interest on the cast iron family. These cast irons (DCIs) combine the good castability of gray irons and high toughness values of steels; they are also characterized by an interesting fatigue crack propagation resistance. Considering their interesting mechanical properties, DCIs are widely used in the critical automotive parts (e.g., crankshafts, truck axles, etc.), and in many other application, like pumps, pipes or turbine components. DCIs can be considered as special-type composites, with graphite nodules embedded in a metal matrix. DCIs performances are strongly affected by the graphite elements morphological peculiarities (e.g., graphite elements nodularity, volume fraction, density, distribution, dimension). Different combinations of the mechanical properties can be obtained depending on the matrix microstructure: focusing on ferritic-pearlitic DCIs, different combination of ductility or tensile strength values can be obtained depending on the phases volume fractions and distribution.

In this work, a ferritic-pearlitic DCI was considered. Compact Type (CT) specimens were metallographically prepared, chemical etched and, then, fatigue precracked and overloaded. According to a step by step procedure, lateral surfaces were observed by means of a Scanning Electron Microscope (SEM) and by means of a Digital Microscope (DM), in order to investigate the influence of the matrix microstructure and of the graphite nodules on damaging micromechanisms.

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Nomenclature

DCI	Ductile Cast Iron

1. Introduction

Damaging micromechanisms in Ductile Cast Irons (DCIs) have been deeply investigated considering both static and quasi static [1-5] and cyclic loading conditions [6-10]. These alloys can be considered as special-type composites, with graphite nodules embedded in a metal matrix. The role played by the graphite elements is quite controversial: some authors enhance the importance of the graphite nodule/matrix debonding and consider the graphite nodules as microvoids embedded in a more or less ductile matrix (depending on the matrix microstructure); other authors propose a more complex role for the graphite nodules, underlying the presence of a mechanical properties gradient inside the graphite nodules with a consequent influence on the damaging micromechanims [11]. Especially considering tensile stress conditions, the influence of graphite nodules on the damaging micromechanisms is matrix dependent: ferritic DCIs are the grades with the lower importance of the graphite elements/matrix debonding mechanism, with the nucleation and growth of secondary cracks inside the nodules and a consequent “onion-like” nodule damaging mechanism.

Considering overload effects on crack propagation and on damaging mechanisms [7, 12], the influence of the matrix microstructure and of the graphite nodules is evident. Considering austempered DCIs [12], decohesion of graphite nodules and the subsequent initiation and growth of microcracks may lead to deflection of the main crack, and the consequent microcracks coalescing process adsorbed energy increase with the applied stress level, with an increase of the crack path tortuosity. Considering a fully pearlitic DCI [7], the authors stressed the generation of a “plastic-damaged zone (instead of a plastic zone, according to LEFM principles), with the presence of secondary cracks and damaged nodules, with an increase of the path tortuosity as the applied (over)load increases.

In this work, a ferritic-pearlitic DCI was considered and the effect of overloads on the damaging micromechanisms ahead of a fatigue crack tip was investigated by means of Scanning Electron Microscope (SEM) and of Digital Microscope (DM) observations of the specimen lateral surface (according to a step-by-step procedure).

The alloy investigated in this work was previously investigated focusing on the fatigue crack propagation micromechanisms [13]: a key-role was played both by the graphite nodules and by their interaction with the monotonic and the cyclic plastic zone. Ahead of the fatigue crack tip, instead of the “classic” plastic zone, a “plastic-damaged” zone seems to be more evident, with the graphite nodules debonding that is the most important damaging micromechanism.

2. Investigated material and experimental and numerical procedure

An as cast ferritic – pearlitic DCI, with analogous ferrite and pearlite volume fraction and showing a classic “bull’s eye” morphology (Fig. 1) and characterized by a high graphite elements nodularity, was investigated (chemical composition is shown in Table 1).

Table 1. Investigated ferritic DCI chemical composition.

C	Si	Mn	S	P	CR	Mg	Sn
3.65	2.72	0.18	0.010	0.03	0.05	0.055	0.035

10 mm thick CT specimens were metallographically prepared and etched (Nital 3), and fatigue precracked ($R=P_{min}/P_{max} = 0.1$). Fatigue precracking was performed using a computer controlled servohydraulic machine in load controlled conditions, 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). After the precracking procedure (measured crack length

equal to 3 mm), decreasing ΔK values were applied according to the relationship:

$$\Delta K = \Delta K_0 e^{\left[C(a-a_0)\right]} \tag{1}$$

where ΔK_0 is the initial ΔK at the beginning of the test (20 MPa√m), a_0 is the corresponding crack length, a is the crack length during the test and C is equal to -0.291. This procedure allowed to obtain a propagating crack with a decreasing crack tip plastic zone radius, up to threshold conditions (about 8 MPa√m), that are characterized by a negligible crack tip plastic zone radius. According to this procedure, it was possible to obtain a crack final length of about 20 mm.

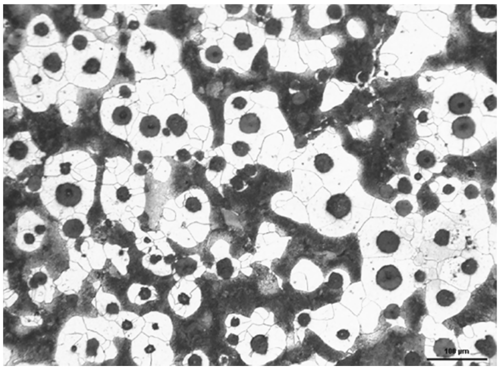

Fig. 1. Investigated ferritic-pearlitic ductile iron: phases distribution (Nital 3).

Subsequently, static overloads were applied according to the following step-by-step procedure:

1) Applied K_I increase was obtained by means of a servohydraulic machine under load control conditions. Corresponding to each overload, COD was measured. Applied K_I values were: 15, 20, 25, 30, 35, 40, 45 MPa√m, respectively.

2) The load was decreased to zero and the specimen was removed from the grips. Using the "screw loading machine" in Fig. 2, the specimen was loaded again up to the same COD value obtained in step 1. This "screw loading machine" allowed to observe the specimen lateral surface by means of a SEM or of a DM under overloading conditions.

In order to investigate the damaging micromechanisms at the crack tip, Scanning Electron Microscope (SEM) and Digital Microscope (DM) specimens lateral surface observations were performed after the overloads. SEM observations were mainly focused on the graphite nodules damaging analysis, while DM allowed a more complete analysis of the damage evolution in the matrix (e.g., by means of the observation of slip bands evolution, sometimes less evident if observed by means of a SEM).

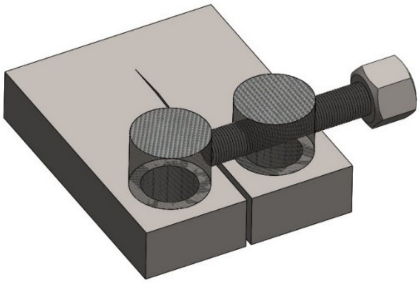

Fig. 2. "Screw loading machine".

In addition, fracture surface SEM analysis was also performed applying a 3D fracture surface reconstruction procedure, in order to analyse the influence of the loading conditions on the fracture surface roughness and, as a consequence, on the damaging micromechanisms. Corresponding to the same specimen position, a stereoscopic image was obtained performing an eucentric tilting around the vertical axis and capturing two different images with a tilting angle equal to 6°. A 3D surface reconstruction was performed by means of Alicona MeX software.

3. Experimental results and discussion

Fig. 3-5 show the results of the DM observations corresponding to K_I values equal to 15, 30, 45 MPa√m, respectively.

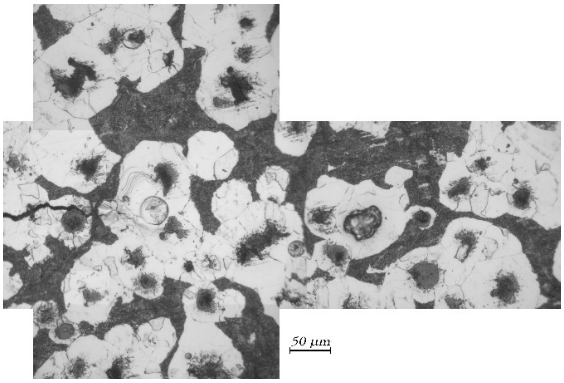

Fig. 3. Crack tip DM lateral observation (after overload; K_I = 15 MPa√m).

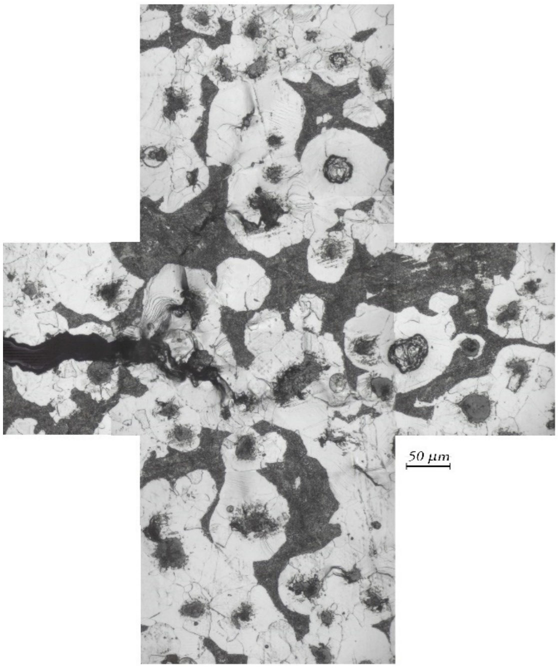

Fig. 4. Crack tip DM lateral observation (after overload; K_I = 30 MPa√m).

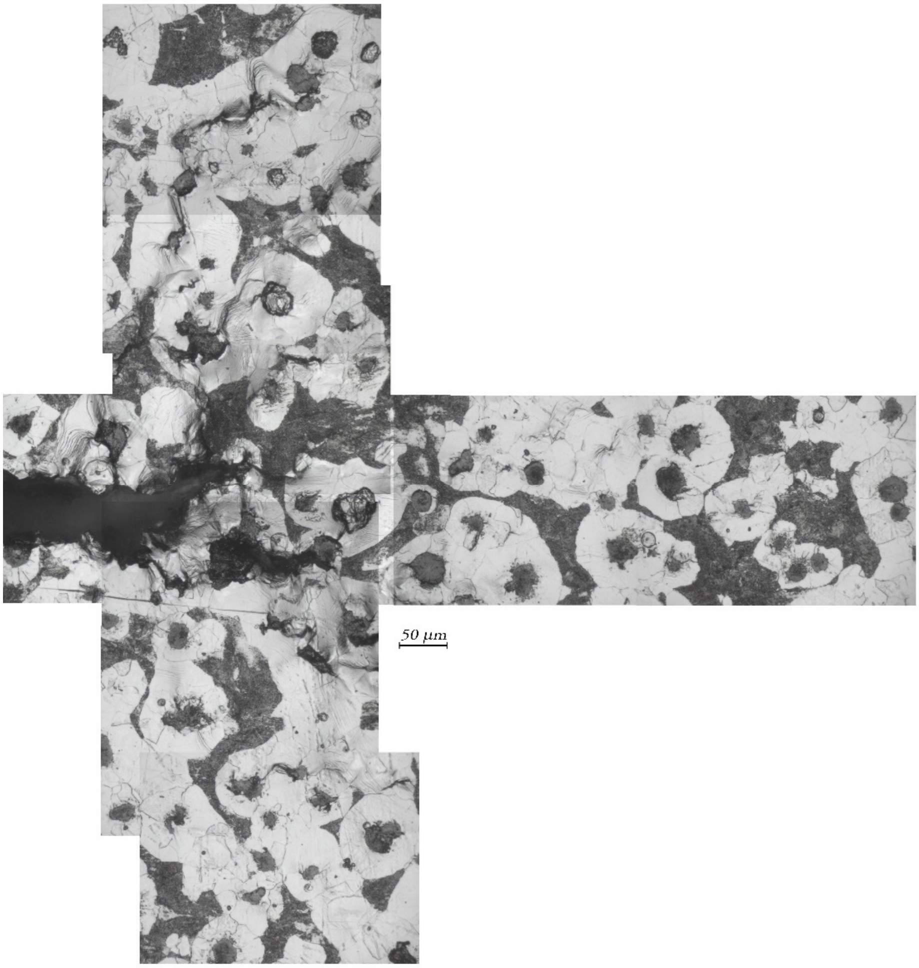

Fig. 5. Crack tip DM lateral observation (after overload; K_I = 45 MPa√m).

Considering the ferritic-pearlitic matrix, it is evident the increase of the importance of the plastic deformation with the increase of the applied K_I, which can be summarized as follows:

- plastic zone radius increases;
- slip bands become more and more numerous and evident;
- slip bands shape is strongly influenced by the graphite nodules presence;
- crack propagates (but this is more evident with the SEM observations);
- in the plastic zone, secondary cracks initiate and propagate corresponding to the graphite nodules/matrix interfaces;
- crack tip blunting is larger and larger.

Corresponding to the lower K_I values, slip bands mainly emanate from the crack tip (Fig. 3), but, for higher K_I values, the emanation of the slip bands is also observed corresponding to the matrix/nodules interfaces (Fig.4 and 5). Focusing on the crack propagation and comparing the behaviour of the investigated ferritic-pearlitic DCI with the behaviour of a pearlitic DCI previously investigated [10], it is to be underlined the evident difference between the observed behaviours. The pearlitic DCI is characterized by a stable crack propagation corresponding to each K_I increase, with a reduced crack tip blunting. Instead, the ferritic-pearlitic DCI investigated in this work is characterized by a really reduced crack propagation, with a crack blunting that becomes more and more evident with the increase of the applied K_I. Crack propagation seems to be confirmed as a discontinuous process, with secondary cracks that initiate corresponding to the graphite nodules/matrix interfaces ahead the crack tip and propagate with the increase of the applied K_I value, as shown in Fig. 4 and 5 (DM observations) and in Fig. 6 (SEM observation). As a consequence of the damaging micromechanisms, a damaged/plastic zone is obtained ahead the fatigue crack tip with a radius that increases with the increase of the applied K_I.

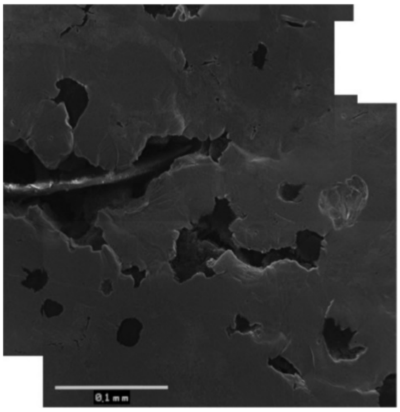

Fig. 6. Crack tip SEM lateral observation (after overload; $K_I = 45$ MPa√m).

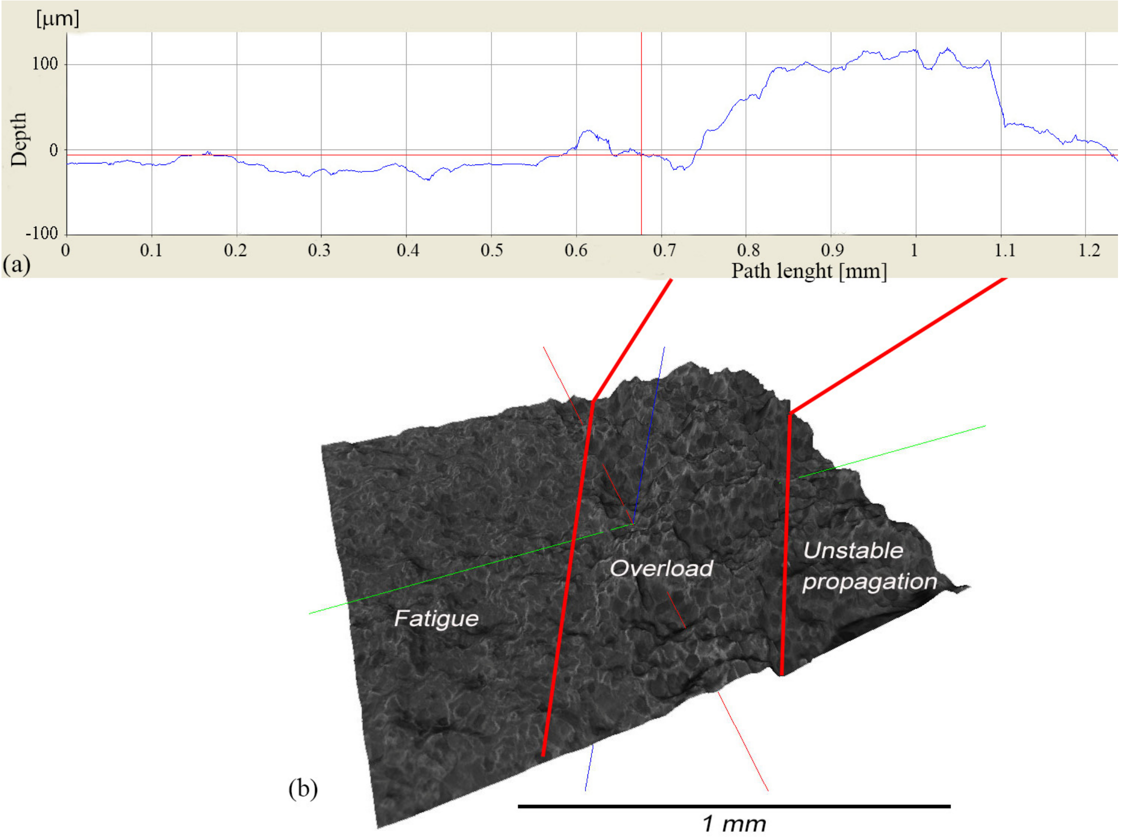

Fig. 7. a) Profile analysis; b) 3D SEM fracture surface observation.

3D fracture surface analysis shows the difference between the fatigue crack propagation stage and the crack propagation due to the overloads (Fig. 7a). Fatigue crack surface is characterized by a smoother fracture surface with respect to the fracture surface obtained as a consequence of the overloads (stable propagation) or during the failure (Fig. 7 and 8). It is interesting to note that, ahead the fatigue crack tip in Fig. 7b (smoother zone), it is possible to observe a zone that is characterized by the higher roughness values (about 400-500 µm thick). After this zone, roughness values decrease, although they are still higher that the values observed in the fatigue crack propagation zone. The thickness of the zone with the highest roughness values is comparable with the plastic/damaged zone obtained with the overloads (Fig. 5).

Differences between the fracture surface obtained during the fatigue propagation and the fracture surface due to the overloads are more evident in Fig. 8a and 8b respectively (same magnification). Due to the higher triaxiality level, the matrix/graphite nodules debonding obtained during the overloads seems to be more developed with respect to the debonding obtained during the fatigue crack propagation. An example can be shown in Fig. 9a and 9b where a volume analysis is performed on two voids due to matrix/graphite element debonding (in the fatigue stage and in the overload stage, respectively).

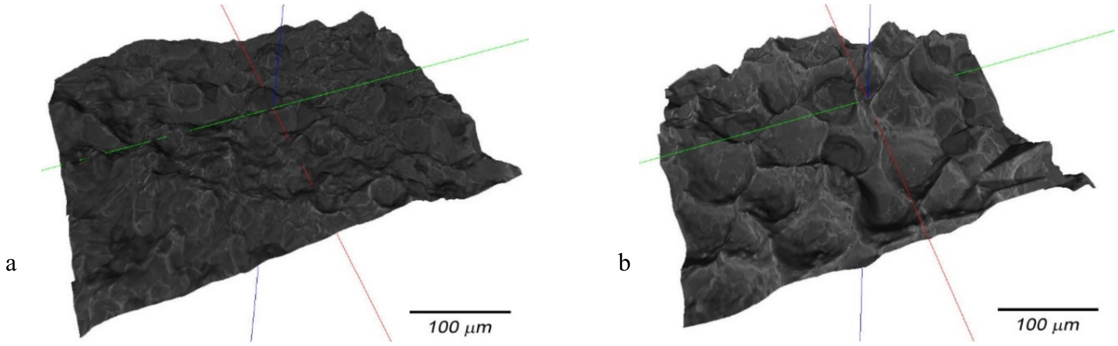

Fig. 8. 3D SEM observations: a) fatigue fracture surface; b) overload fracture surface.

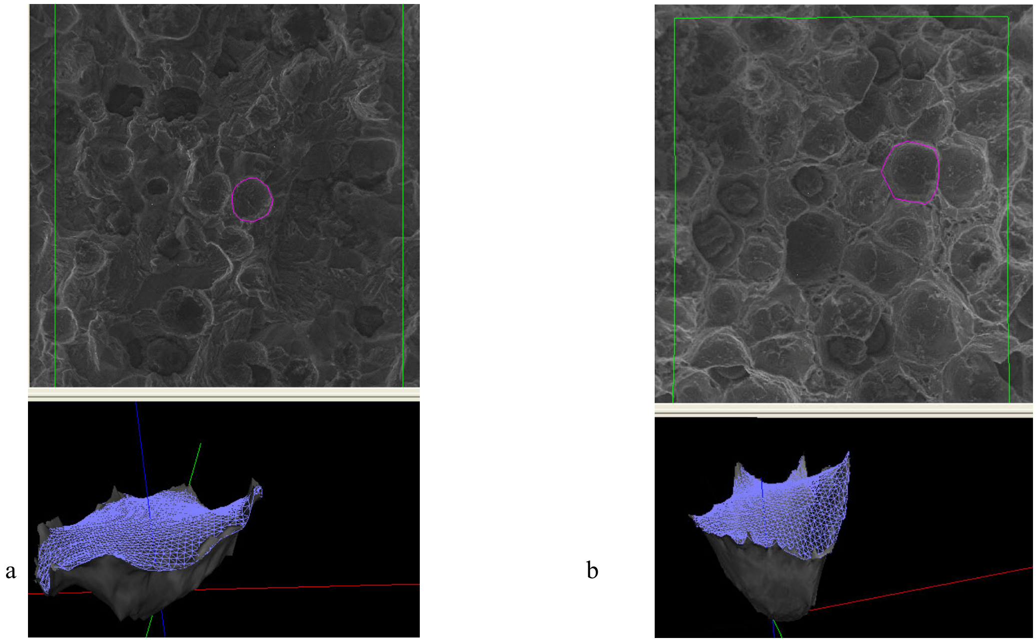

Fig. 9. 3D volume analysis performed on void due to matrix/nodule debonding: a) fatigue stage; b) overload stage.

4. Conclusions

In this work, the overload effects on a fatigue crack in a ferritic-pearlitic DCI were investigated by means of SEM and DM observations of the lateral surface of CT specimens, following a step-by-step procedure. According to the experimental results, the following conclusions can be summarized:

- Due to the overloads, crack blunting seems to be an evident mechanism;
- Crack propagation during overloads is quite reduced the increase of the crack tip plastic zone (e.g., slip bands) is more evident, as well as the initiation and growth of secondary cracks (debonding between graphite nodules and ferritic-pearlitic matrix); instead of a crack tip plastic zone it is more realistic to describe a crack tip damaged/plastic zone;
- The crack tip damaged/plastic zone can be easily observed by means of a 3D reconstruction of the fracture surface, due to its higher roughness.

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