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Overload effects on fatigue cracks in ferritic-pearlitic ductile cast irons

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Abstract

Matrix microstructure (e.g., phases volume fraction, grains size and grain distribution) and graphite nodules morphology peculiarities (e.g., nodularity level, dimension, distribution etc.) strongly affect the mechanical behavior and damaging micromechanisms in Ductile Cast Irons (DCIs). Concerning the influence of the graphite nodules, it depends both on the matrix microstructure and the loading conditions (e.g., static, quasi-static or cyclic loadings). The influence of graphite nodules on the damaging micromechanisms is not univocally identified. Some authors proposed to consider the graphite nodules as voids embedded in a more or less ductile matrix; other authors recently proposed a more complex contribution of the graphite nodules, suggesting a mechanical properties gradient inside the graphite nodules, with the graphite elements – matrix debonding as only one of the possible damaging micromechanisms.
In this work, three different ferritic-pearlitic DCIs were investigated, focusing the damaging micromechanisms due to overloads applied on fatigue cracked Compact Type specimens. Scanning Electron Microscope (SEM) and Digital Microscope (DM) observations were performed on the lateral surfaces of the overloaded specimens following a step by step procedure: SEM observations were mainly focused on the damaging mechanisms in graphite nodules; DM observations were mainly focused on the damaging mechanisms in the ferritic-pearlitic matrix.

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

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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). DCIs are able to combine the more peculiar cast irons property (castability) with toughness of carbon steels. Versatility and higher performances at lower cost if compared to steels with analogous performances are the main DCIs advantages. Nowadays, DCIs are mainly 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 more critical applications as containers for storage and transportation of nuclear wastes. Matrix controls mechanical properties and matrix names are used to designate spheroidal cast iron types, [Jeckins and Forrest (1993), Ward (1962), Labreque and Gagne (1998)]. Different DCIs grades are commercially available. Among them, the most common DCI grades are characterized by ferritic, pearlitic and ferritic-pearlitic. Ferritic DCIs grades are characterized by good ductility and a tensile strength that is more or less equivalent to that of a low carbon steel. Pearlitic DCIs show higher strength values, good wear resistance and moderate ductility. Finally, ferritic–pearlitic grades properties are intermediate between ferritic and pearlitic ones. As far as the fatigue crack propagation resistance is concerned (Fig. 1), the ferritic-pearlitic DCI seems to be characterized by the best behaviour, at least for higher R and ΔK values.

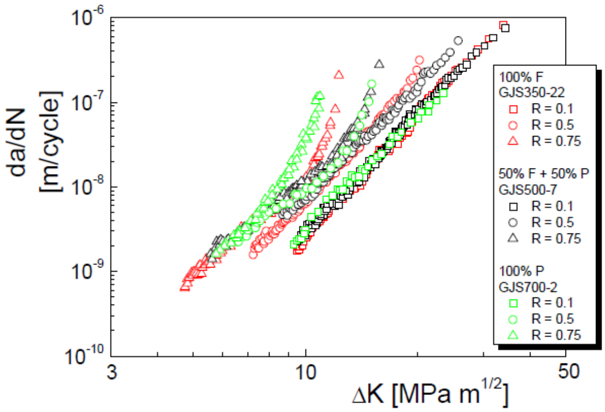

Fig. 1 Microstructure and stress ratio influence on fatigue crack propagation, Di Cocco (2013).

Focusing the fatigue crack propagation resistance, considering both the initiation and propagation of micro- and macro- cracks, the role played by graphite nodules is not univocally determined. Some of the main proposed roles, depending on the matrix microstructure, are:

- Irregularities on graphite nodules surfaces plays the role of stress raisers with the nucleation and growth of microcracks and a consequent branched morphology of the crack path [Greno et al. (1999), Yang and Putatunda (2005)];
- Graphite nodules that are considered as 'rigid spheres' not bonded to the matrix and acting like voids under stress, Rabold and Kuna (2005).
- As a consequence of the nodule-matrix debonding, the overall crack path tortuosity increases, with possible shielding effects, Stokes (2007).
- Graphite nodules as 'crack closure effect raisers', due to their influence on the crack closure effect corresponding to lower K values, Cavallini et al. (2008) and Iacoviello et al. (2010).
- Due to the solidification mechanisms, graphite nodules are characterized by a mechanical properties gradient (e.g., hardness and wearing resistance): microcracks nucleate and growth inside the graphite nodules, especially considering high triaxiality stress levels, Iacoviello et al. (2013).

Although the graphite obtained during the solidification and cooling processes is crystallographically homogeneous, results obtained by means of different experimental procedure (e.g., nanoindentation tests and wearing resistance tests) confirm the presence of the internal mechanical properties gradient in graphite nodules, Pradhan et al. (2009) and Randall et al. (2009).

In this work, three different ferritic-pearlitic DCIs were considered and the effects of overloads on the damaging micromechanisms ware investigated by means of Scanning Electron Microscope (SEM) and of a Digital Microscope (DM) observations of lateral surface of fatigue cracked Compact Type specimens.

2. Investigated material and experimental and numerical procedure

Three different spheroidal cast iron grades were considered: ferritic DCI (GJS 350-22), pearlitic DCI (GJS 700-2) and ferritic-pearlitic DCI (GJS 500-7). Chemical composition are shown in Tables 1-3. All the investigated DCIs are characterized by a good nodularity (higher than 85%).

Table 1. Investigated fully ferritic DCI chemical composition (GJS 350-22).

C	Si	Mn	S	P	Cu	Cr	Mg	Sn
3.62	2.72	0.19	0.011	0.021	0.019	0.031	0.047	0.011

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

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

Table 3. Investigated ferritic-pearlitic DCI chemical composition (GJS 500-7).

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 metallographical prepared (Nital 3) and fatigue precracked using a computer-controlled servohydraulic machine in constant load amplitude and 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 gauge and controlled using an optical microscope (40x). After the precracking procedure (final crack length equal to 15 mm), decreasing ΔK values were applied according to the relationship:

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

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.

After the fatigue precracking procedure, static overloads were applied according to the following step-by-step procedure:

1) A servohydraulic machine under load control condition was used in order to apply increasing stress intensity factor values, K_I. The investigated K_I values were respectively:

- For fully ferritic DCI (GJS 350-22): 15, 20, 25, 30, 35, 40 MPa√m;

- For fully pearlitic DCI (GJS 700-2): 15, 20, 25, 30, 35 MPa√m;
- For ferritic-pearlitic DCI (GJS 500-7): 15, 20, 25, 30, 35, 40, 45 MPa√m.

2) Corresponding to each overload, COD values were measured. Subsequently, load was decreased to zero, the specimen was removed from the grips and it was loaded again up to the same COD value obtained in step 1 using a "screw loading machine" (Fig. 2). This machine allowed to observe the specimens lateral surface by means of a Scanning Electron Microscope (SEM) or of a Digital Microscope (DM) under overloading conditions. Observations were mainly performed ahead the crack tip zone. SEM observations were focused mainly, but not uniquely, on the graphite nodules damaging analysis, whereas DM observations were focused mainly, but not uniquely, on the matrix damage evolution.

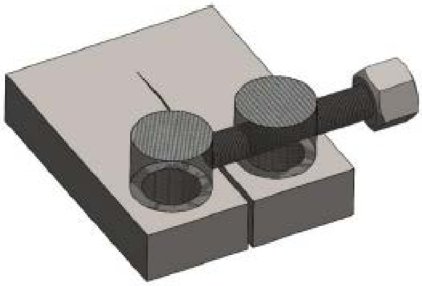

Fig. 2 "Screw loading machine".

In addition, a 3D fracture surface reconstruction was performed in order to analyze the influence of the loading conditions on the fracture surface roughness and, as a consequence, on the damaging micromechanisms. Using SEM, 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°. Then, a 3D surface reconstruction was obtained by means of Alicona MeX software.

3. Experimental results and discussion

The effect of the increasing K_I values on the stable crack propagation in ferritic-pearlitic DCIs is affected by the matrix microstructure.

Considering the pearlitic DCI, the increase of the applied K_I value implies macroscopically a stable propagation with a discontinuous mechanisms, with the crack path characterized by a high tortuosity (higher than the fatigue crack propagation stage, Fig. 3). Focusing on the graphite nodules, depending on the distance from the crack tip, it is possible to identify two different behaviors:

- near the crack tip, internal damage is evident, both as radial cracks and as internal debonding between a nodule core and a nodule shield (analogously to the mechanism observed during the fatigue crack propagation);
- far from the crack tip, where the debonding between the graphite nodules and the pearlitic matrix is the main damaging micromechanisms.

Focusing on the ferritic-pearlitic DCI, during overloads crack propagation is quite reduced and crack tip blunting seems to be an evident mechanism (Fig. 4). The increase of the applied K_I value implies macroscopically an increase of the plastic deformation, with an increase of the crack tip plastic zone radius. In the plastic zone it is possible to observe the presence of slips bands and secondary cracks (e.g. debonding between graphite nodules and ferritic-pearlitic matrix) initiate corresponding to the matrix/nodules interfaces and become more numerous and evident with the increase of the applied K_I value. In this case, due to the damaging micromechanisms, it is better to describe a crack tip damaged/plastic zone instead of crack tip plastic zone.

Considering the ferritic DCI, it is important the increase of the plastic deformation with the increase of the applied K_I value. Overloads imply macroscopically a large damaged zone near the crack tip with the presence of slip bands, mainly near the graphite nodules, and numerous secondary cracks, both in the ferritic matrix and in graphite nodules, become more evident with the increase of the applied K_I value (Fig. 5-6). For the overloading conditions, the stress intensity factor *K,* used to quantify the stress state near the crack tip caused by a remote load or residual stresses, should be critically reconsidered; ferritic DCI cannot be considered as a homogeneous and linear-elastic body because plastic radius is much higher than graphite nodule diameters. Due to 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.

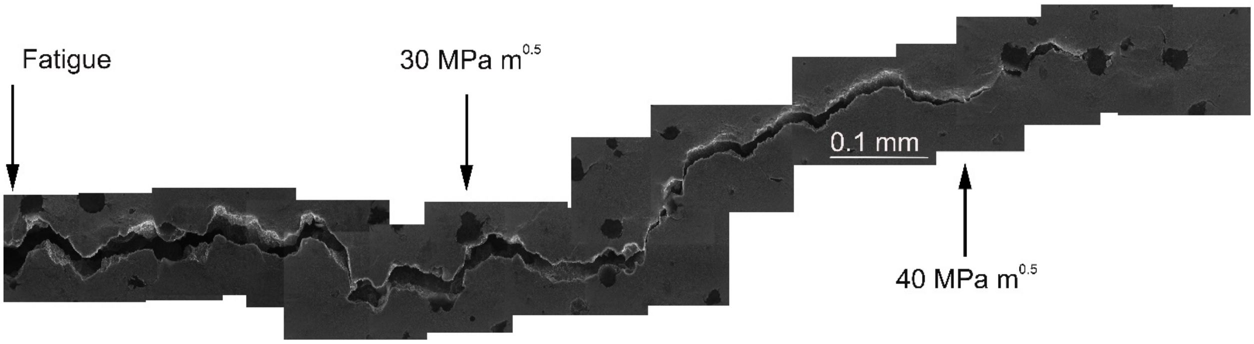

Fig.3 Crack tip SEM lateral observation in pearlitic DCI, corresponding to K_I =45 MPa√m. Arrows show the stable crack propagation due to fatigue and to intermediate K_I values (e.g. 30 and 40 MPa√m).

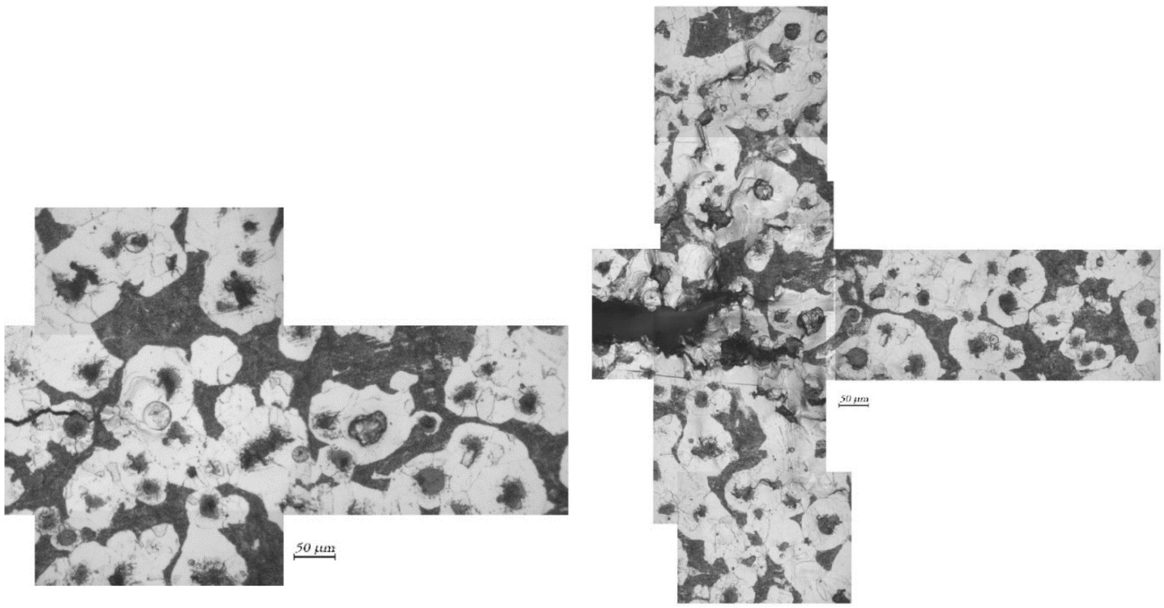

Fig.4 Crack tip DM lateral observation in ferritc-pearlitic DCI, on the left K_I =15 MPa√m, on the right K_I =45 MPa√m.

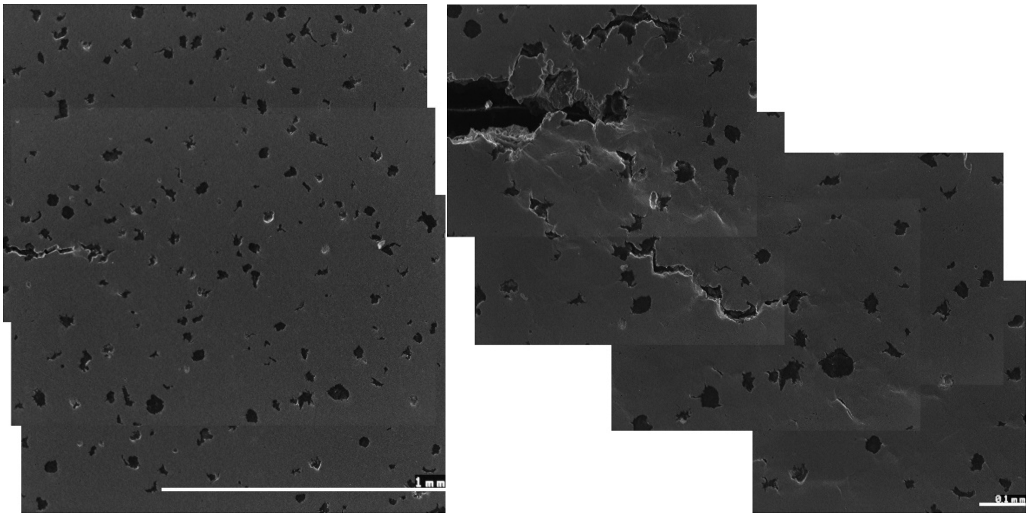

Fig.5 Crack tip SEM lateral observation in ferritic DCI, on the left K_I =20 MPa√m, on the right K_I =35 MPa√m.

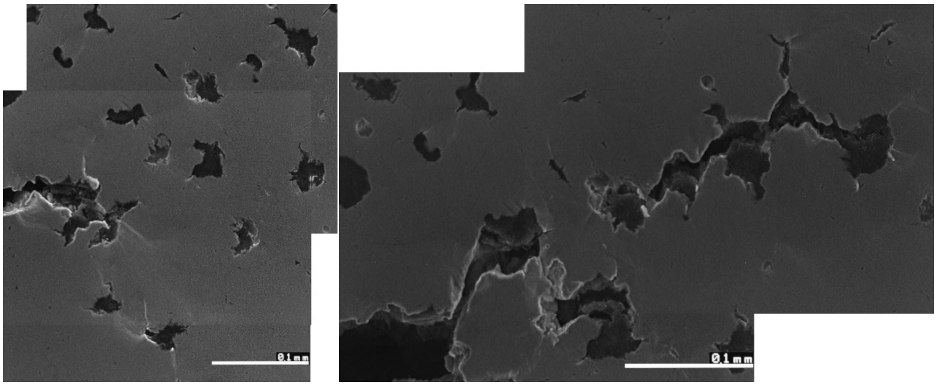

Fig.6 Crack tip SEM lateral observation in ferritic DCI on the left K_I =20 MPa√m, on the right K_I =30 MPa√m.

Focusing on the crack propagation during the application of overloads and comparing the behavior of the investigated ferritc-pearlitc DCIs, it can be assumed that:

- Pearlitic DCI shows a stable crack propagation corresponding to each K_I value, with a reduced crack tip blunting;
- Ferritic-pearlitic DCI is characterized by a reduced crack propagation, with a crack blunting that becomes more and more evident with the increase of the applied K_I.
- Ferritic DCI 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.

Considering the graphite nodules, it is possible to identify two main damaging micromechansims, depending on the distance from the crack tip:

- near the crack tip it is possible to observe an internal damage, due to radial cracks and an internal debonding between a nodule core and a nodule shield, Fig.7;
- far from the crack tip, the debonding between the graphite nodules and the pearlitic matrix is the main damaging micromechanisms.

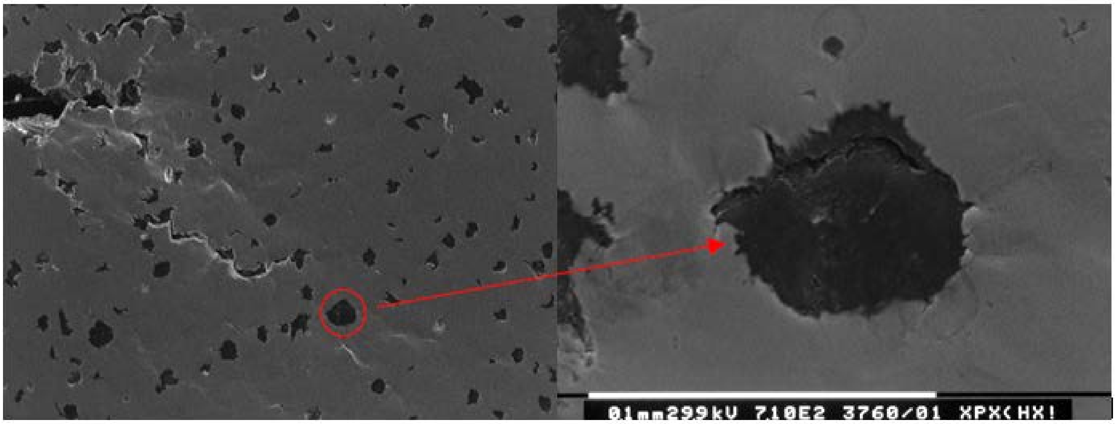

Fig.7 Graphite nodule internal debonding in ferritic DCI after overload K_I =35 MPa√m.

Thanks to the 3D fracture surface analysis is it possible to observe the difference between the fatigue crack propagation and the crack propagation due to overloads. This zone can be easily recognized because it is characterized by higher roughness values and, at the same time, by an increment of graphite nodules, Fig.8. In fact, this increase is due to the fact that, with the increase of the applied K_I, the increase of the damage in the demage/plastic zone ahead the fatigue crack tip implies, in the graphite nodules, a lower resistance path to crack. It follows a greater evidence of nodules on fracture surface compared to the fatigue crack propagation.

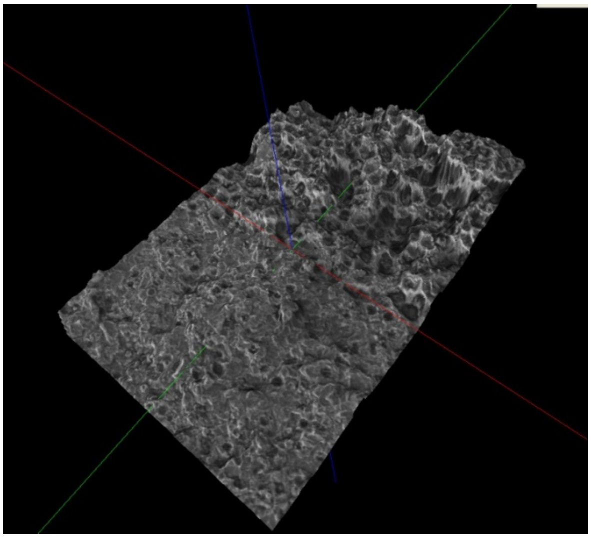

Fig.8 SEM observation of the fracture surface in ferritic DCI.

Conclusions

In this work, three different ferritic-pearlitic DCIs were investigated in order to analyze damaging micromechanisms due to overloads. In order to achieve this goal, observations on the lateral surfaces of fatigue cracked Compact Type specimens were performed focusing the attention both on the matrix (by means of DM 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 on the crack propagation, pearlitic DCI shows the most evident crack propagation with a reduced crack tip blunting instead ferritc DCI shows the less evident crack propagation with a higher crack blunting. Ferritic-pearlitic DCI behavior is intermediate between ferritic and pearlitic grades;
- focusing the graphite nodules, two main damaging micromechanisms have been identified, mainly dependent on the distance from the crack tip;
- the damaged/plastic zone ahead the fatigue crack tip is characterized by a higher roughness compared with the fatigue crack propagation and it can be easily recognised by means of 3D reconstruction.

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