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Pearlitic ductile cast iron: fatigue crack paths and damaging micromechanisms

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Abstract

The influence of the graphite nodules morphology (shape, dimension and distribution) on ductile cast irons (DCIs) mechanical properties is experimentally confirmed both in static, quasi static and cyclic loading conditions. According to the most recent results, these graphite elements cannot be merely considered as ''microvoids embedded in a metal matrix'', but their presence implies a modification of the damaging micromechanisms and this modification I s influenced by the metal matrix microstructure. In this works, the different damaging mechanisms that are active in the graphite nodules in a pearlitic DCI are semi-quantitatively analyzed using light optical microscope observations of the fracture surface profiles.

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Keywords: Pearlitic Ductile Cast Irons; Damaging micromechanism; Fatigue crack propagation

1. Introduction

Ductile Cast Irons (DCIs) damaging micromechanisms are influenced by the matrix microstructure, by the graphite elements nodularity and by the loading conditions (e.g., Cavallini et al. (2008), Gonzaga (2013), Hütter et al. (2015), Iacoviello and Di Cocco (2016), Di Cocco and Iacoviello (2017)). Ranging from static or quasi static to cyclic loading conditions, and considering different matrix microstructures, from fully ferritic to fully pearlitic, the main observed damaging micromechanisms can be classified as follow:

Graphite nodules:

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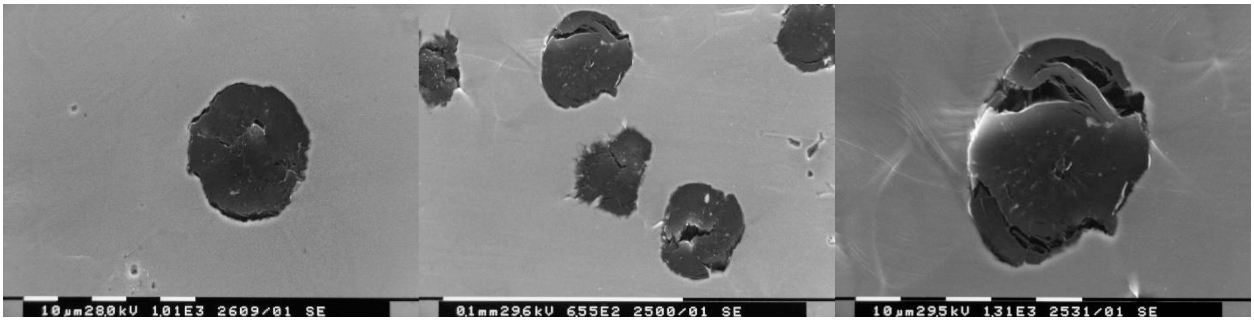
- Matrix-graphite elements debonding: described by Dong et al. (1997), it is the most considered damaging in the in the simulation process, although it is only seldom observed in ferritic rich microstructures (Fig. 1a).
- Crack initiation at the nodule center, probably corresponding to a solidification site (e.g., a non metallic inclusion), followed by a crack propagation with a consequent graphite nodule “disaggregation” (Fig. 1b).
- Crack initiation corresponding to the interface between a nodule “core” (characterized by lower microhardness values) and a nodule “shield” followed by a crack propagation according to an “onion-like” mechanism (Fig. 1c).



a b c

Fig. 1. Damaging micromechanisms:(a) matrix-nodule debonding; (b) crack nucleation and propagation in the nodule center; (c) “Onion-like” mechanism.

Nomenclature

DCI	Ductile Cast Iron
SEM	Scanning Electron Microscope

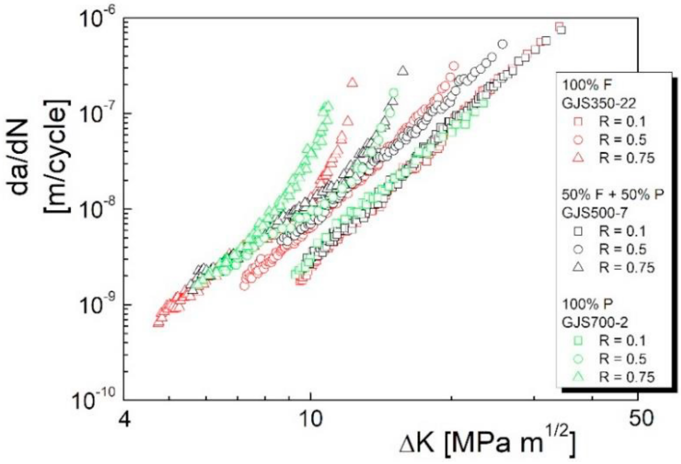


Fig. 2. Ferritic-pearlitic DCIs. Microstructure and stress ratio influence on fatigue crack propagation, Cavallini et al. (2008).

Matrix:

- Slip bands emanating at the nodule equator with consequent crack initiation in the matrix;
- Crack propagation followed by crack-crack and/or crack-damaged nodules coalescence.

Considering the fatigue crack propagation, Cavallini ed al. (2008) showed that, in the da/dN-ΔK diagram, the influence of the microstructure is almost negligible corresponding to the lower ΔK and/or R values and become more and more evident for higher ΔK and R values, being the pearlitic DCI characterised by the worst behaviour (higher slope of the Paris stage and lower ΔK_{max}, Fig. 2).

In this work, the influence of the applied ΔK on the importance of the different damaging mechanisms in the graphite elements has been investigated by means of light optical microscope observations of transversal sections of the fracture surfaces obtained performing fatigue crack propagation tests on Compact Type specimens.

2. Investigated alloy and experimental procedure

Investigated DCI chemical composition is shown in Table 1 (EN GJS700-2). Graphite elements in the investigated pearlitic DCI were characterized by a very high nodularity, higher than 85%, with a volume fraction of about 9-10%.

Table 1. Ductile cast iron EN GJS700-2 chemical composition (5% ferrite – 95% pearlite).

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

Fatigue crack propagation tests were run according to ASTM E647 (2011) standard, using 10 mm thick CT (Compact Type) specimens. Tests were performed using a computer-controlled servo hydraulic machine in constant load amplitude and constant stress ratio ($R = P_{min}/P_{max} = 0.1$) 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). Fatigue crack propagation tests were repeated three times.

After the fatigue crack propagation tests, fracture surfaces were nickel coated, in order to protect the surfaces by the following cutting procedure. Transversal sections were obtained corresponding to three different ΔK values (10, 15 and 20 MPa √m, respectively) and, after a metallographic preparation, they were observed by means of a light optical microscope (LOM) with a 200x magnification. For each transversal section, the fracture profiles were completely analyzed and all the nodules on the profile were classified considering the observed damaging micromechanisms (matrix-nodule “pure” debonding, “onion-like” mechanism and nodule disaggregation mechanism, according to Fig. 1).

3. Experimental results and discussion

The results in the da/dN-ΔK diagram are characterized by a very low scatter of the crack growth rate values for the same ΔK values.

Some examples of the LOM observations of the fracture profiles are shown in Figs. 3-5. Different profiles were observed during the analysis and different fracture morphologies were classified:

1) matrix – nodules “pure” debonding: nodules partially embedded in the pearlitic matrix with their original nodular shape (Fig. 3, blu arrow) and voids on the fracture surfaces that can be clearly related to a nodule, without graphite residuals (Fig. 3, red arrow).

2) also for the “onion like” mechanism two different morphologies were observed: nodules that are partially embedded in the pearlitic matrix but partially lost their original shape (Fig. 4, green arrow) and voids on the fracture surfaces that can be clearly related to a nodule, with graphite residuals.

3) The last observed mechanism can be related to the “disaggregation” mechanism, with the nodules that are partially embedded in the pearlitic matrix but completely lost their original nodular shape (Fig. 5, orange arrow).

The results of the LOM observations for the three investigated ΔK values can be summarized in Fig. 6, with the % of each damaging mechanism (e.g., DM%) that is measured as the ratio between the number of the nodules (and voids) characterized by the observed damaging mechanism (debonding, onion-like or disaggregation) and the total number of the nodules (and voids) that are observed in the investigated transversal section of the fracture surface.

According to the experimental results in Fig. 6, it is worth to note that for each investigate ΔK value, the damage % evaluation is characterized by a high repeatability, showing the results a quite low dispersion. Applied ΔK seems to have a negligible influence on the importance of each damaging mechanism. For example, for the most important damaging mechanism (debonding), the mean values of the DM% range between 57 and 61%.

Analogously to the main damaging mechanism that is active in pearlitic DCIs during a tensile test, Di Cocco et al. (2014), matrix – nodules debonding is confirmed as the most important damaging micromechanism (some examples of matrix – nodules debonding are shown in fig. 7). Anyway, the contribution of the other two mechanism can't be considered as negligible, especially considering the onion-like mechanism, being the mean value of the DM% between 28 and 30%. The contribution of the disaggregation mechanism is lower, ranging between 9 and 13%.

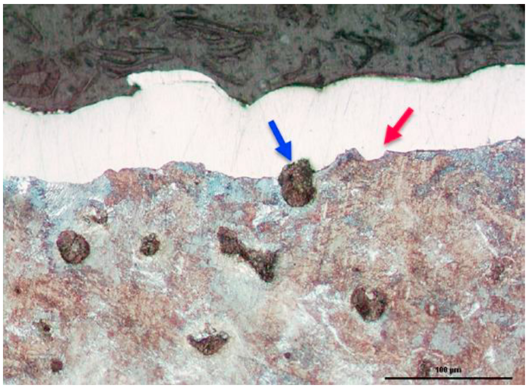


Fig. 3. Pearlitic matrix – graphite nodules pure debonding.

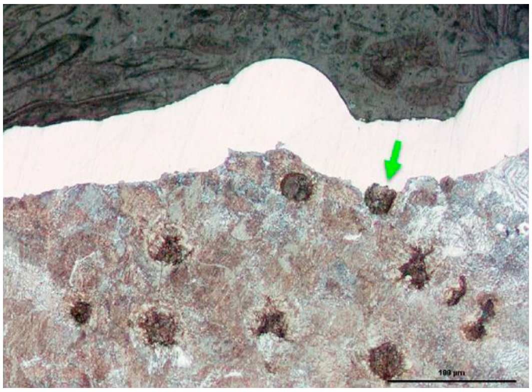


Fig. 4. "Onion-like" mechanism.

Fig. 5. "Disaggregation" mechanism. The arrow shows the residual of a cracked graphite nodule.

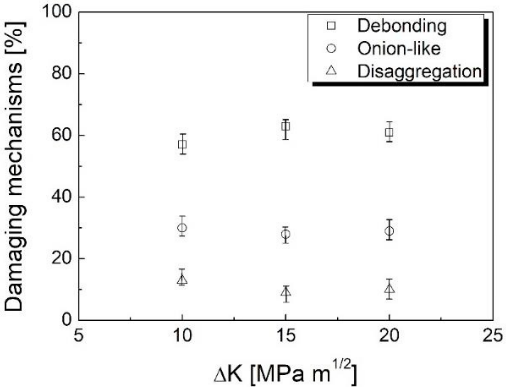


Figure 6: Fatigue crack propagation in a pearlitic DCI. Different damaging micromechanisms corresponding to graphite nodules.

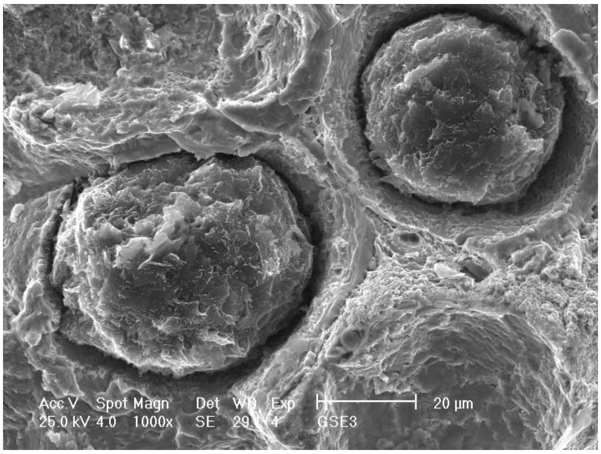


Figure 7: SEM fracture surface analysis: graphite nodules – pearlitic matrix debonding.

Always considering the experimental results, the number of the nodules (and voids) on the crack profile increases with the increase of the applied ΔK, ranging from a mean value of about 55 nodules (and voids) for ΔK = 10 MPa √ m up to about 70 nodules (and voids) for ΔK = 20 MPa √ m. Remembering that an increase of the fracture surface roughness was observed with the increase of the applied ΔK during a fatigue crack propagation in DCI [Iacoviello et al. , 2000], this implies that graphite nodules can't be merely considered as voids embedded in a pearlitic matrix or as particle with a negligible mechanical resistance, but they are able to influence the fatigue crack path and, as a consequence, the fatigue crack propagation resistance. Considering that the graphite linear temperature expansion coefficient (LTEC) is lower than the values offered by the pearlitic matrix (between 4 and 8 K^{-1} for graphite, about 10.9 K^{-1} for pearlitic steels, www.repairengineering.com), during the cooling process after the solidification, the differences in LTEC values implies the initiation of a compressive stress state in the graphite elements that is equilibrated by a tensile stress state in the pearlitic matrix (considering that $\Sigma\sigma = 0$). The decrease of the temperature during the cooling stage up to the room temperature increases the importance of this internal stress state (compression in graphite elements, tensile in pearlite around the nodules). According to the authors, it is possible to propose that, during the fatigue crack propagation, the crack path can be strongly influenced by this stress state. In fact:

- Corresponding to lower ΔK values, when the graphite nodules diameters are comparable with the main fracture mechanics geometrical parameters (e.g. crack tip plastic zone corresponding to K_{Imax} and reversed plastic zone) the influence of the graphite nodules on the crack paths is low and the fatigue crack is not "attracted" by the graphite nodules with a consequent reduced fracture surface roughness.
- For higher ΔK values, the main fracture mechanics geometrical parameters (e.g. crack tip plastic zone corresponding to K_{Imax} and reversed plastic zone) are larger and can influence the crack path. The interaction between the stress field ahead the crack tip interacts with the stress field around the nodules with a simply consequence: the fatigue crack seems to be "attracted" by the graphite nodules with the consequent increase of the fracture surface roughness (obtaining more nodules on the fracture surface!)

Focusing the damaging mechanisms, they do not seem to be influenced by the applied ΔK values. According to the authors at least three parameters should be considered as the most important to activate one of the three observed mechanisms:

- the graphite nucleation process (gas bubbles, non metallic particles etc) that have an influence on the activation of the disaggregation process;
- graphite nodularity and/or the presence of degenerated graphite;
- the position of the crack with respect to the graphite nodules. Some preliminary results showed that when the fatigue crack "meets" the nodule corresponding to the equator zone, the probability of the activation of the "onion-like" mechanism is higher. When the interaction crack vs nodule is near the nodule "polar cap", the probability of the activation of the matrix-nodule debonding is higher. Unfortunately, these are only preliminary results, not confirmed by a systematic experimental observation.

Conclusions

In this work, the influence of the applied ΔK on the importance of the different damaging mechanisms in the graphite elements has been investigated by means of LOM observations of transversal sections of the fracture surfaces obtained performing fatigue crack propagation tests in a pearlitic DCI. According to the experimental results it is possible to summarize that:

- The importance of the three damaging mechanisms observed corresponding to graphite nodules (debonding, onion-line and disaggregation) is not influenced by the applied ΔK.
- Graphite elements-ferritic matrix debonding is the most important mechanism.

Finally, considering the differences in linear temperature expansion coefficients, the presence of a residual stress state at room temperature (compression corresponding to the nodules, tensile in the pearlite around the nodules) has been proposed. According to the authors, this residual stress state can strongly influence the fatigue crack path, becoming more and more tortuous with the increase of the applied ΔK.

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