Damaging micromechanisms in a ferritic ductile cast iron

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Abstract. Ductile cast irons (DCIs) combine the good castability of gray irons and the toughness of steels. This is due to their peculiar graphite elements shape, obtained by means of a chemical composition control and not by means of extended annealing treatment of white irons as in malleable irons. DCIs are widely used in a number of applications, e.g. wheels, gears, crankshafts in cars and trucks etc.; ferritic DCIs are characterized by good ductility, with tensile strength values that are equivalent to a low carbon steel.

In this work, damaging micromechanisms in a ferritic DCI have been investigated by means of in–situ scanning electron microscope observations. Specimens were ground and polished and pulled intermittently with a tensile holder and observed in situ using a scanning electron microscope (SEM), considering 21 graphite nodules. During tests, 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.

On the basis of the experimental results, the following conclusions can be summarized:

voids growth due to graphite spheroids – ferritic matrix debonding seems to have a reduced importance; cracks initiation and propagation inside graphite spheroids seems to be a more important damaging micromechanism.

Other graphite nodules damaging micromechanisms have been observed, like an “onion-like” one.

Introduction

Ductile cast irons are characterized by a wide range of mechanical properties, mainly depending on microstructural factors, as phases (characterized by volume fraction, size and distribution), graphite particles (characterized by number, size and shape) and defects (as porosity, inclusions, segregated elements etc.). Ductile cast irons advantages that have led to its success are numerous, and they can be easily summarized: versatility and higher performances at lower cost. Their versatility is especially evident in the area of mechanical properties where ductile cast irons offer to designers the option of choosing high ductility (up to 18% elongation), or high strength, with tensile strengths exceeding 825 MPa. Austempered ductile iron offers even greater mechanical properties and wear resistance, providing tensile strengths exceeding 1600 MPa.

Focusing tensile strength, DCIs behaviour is similar to that of carbon and low alloy steels. Chemical composition, matrix microstructure and graphite nodules morphology and distribution strongly affect mechanical properties. Matrix could range from fully ferritic, to fully pearlitic, from martensitic to bainitic depending on the chemical composition and on the heat treatment. Ferritic-pearlitic ductile irons are widely used because they are able to summarize both a high castability and good mechanical proper-ties. Ferrite-pearlite volume fraction influence on tensile strength is shown in Fig. 1 [6].

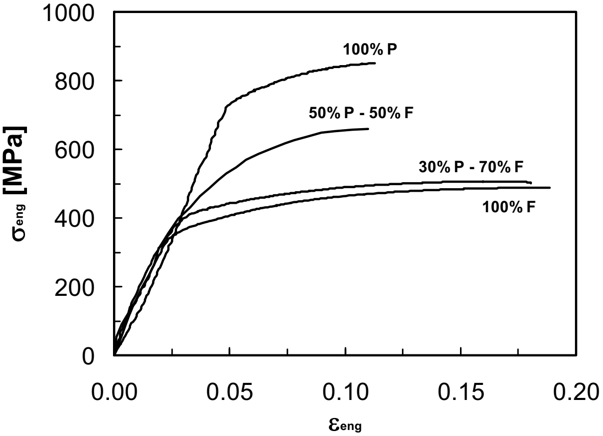

Fig. 1: Ferrite-pearlite volume fraction influence on DCIs tensile strength [6].

Concerning graphite elements shape, a very high nodularity is strongly recommended. The peculiar morphology of graphite elements in ductile irons is responsible of their good ductility and toughness. Characterized by a rough spherical shape, graphite particles contained in ductile irons are also known as “nodules”. They act as “crack arresters”, with a consequent increase of toughness, ductility and crack propagation resistance [1, 2].

DCIs main damage micromechanism is often identified as voids growth corresponding to graphite nodules and numerous studies provided analytical laws to describe growth of a single void, depending on the void geometries and matrix behavior [3-6]: as a consequence, spheroids role is completely neglected. Considering almost fully ferritic DCIs, Berdin et al. [7] proposed that these DCIs should be essentially considered as porous materials, graphite nodules being considered as voids in an elastic–plastic matrix. Microcracks in graphite nodules were also observed, but their presence was not considered as important. Damage main micromechanism was identified with graphite–matrix debonding, and all the other mechanisms were considered as negligible.

In this work, microtensile specimens of a fully ferritic DCI were investigated by means of step by step tensile tests. Specimen surfaces were observed in situ by means of a scanning electron microscope (SEM).

Material and experimental procedure

A fully ferritic DCI was considered (chemical compositions is in table 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. Specimens were ground and polished and pulled intermittently with a tensile holder and observed in situ using a SEM, considering 20 graphite elements. During tensile 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. Figs 2a and 2b show the tensile holder and the tensile test machine, respectively.

Each tensile test is performed with constant crosshead speed of 0.15mm/s, and stopped corresponding to six different ε values in order to perform SEM observations.

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).

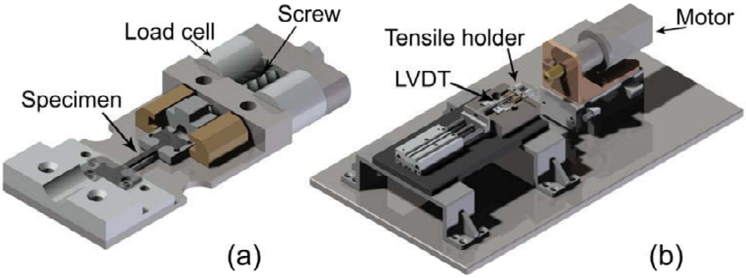

Fig 2: Tensile holder with microtensile specimen (a) and tensile test machine (b).

Experimental results and comments

Figs 3-6 show the damaging evolution in a fully ferritic DCI during a tensile test: points in stress-strain diagrams indicate the corresponding loading conditions; arrows indicate loading direction. Elastic deformation stage does not show an evident damage, neither in ferritic matrix nor in graphite nodules. Focusing graphite nodules, main damaging morphologies could be classified as follows:

- An “onion-like” damage mechanism: nodule shield debonds from nodule core by means of a ductile mechanism (figs 3 and 4); cores diameters are between 75 and 85% if compared to the original graphite spheroids diameters: it is possible to assume a different mechanical behaviour between the nodule “core” obtained directly from the melt [2, 8, 9] and the carbon shield obtained by means of solid diffusion during cooling. High matrix ductility is connected to high graphite spheroids deformation.
- Radial and transversal cracks initiation and propagation: this graphite element damage mechanism usually initiates corresponding to graphite elements with a reduced roundness (Fig. 5); some radial cracks initiate in the nodule core, probably corresponding to graphite solidification nucleation sites (e.g., non metallic inclusions like MgS or CaS [2]; they were not observed, probably due to the adopted specimens preparation procedure);
- Interfacial microcracks at the graphite elements – matrix interface are only seldom observed (e.g, Fig 3c and 4e), and their importance seems to be lower than other graphite elements damaging mechanisms.

All the damaging mechanisms are evident in Fig. 6, where two very close graphite nodules are shown. Cracks propagation inside graphite elements could be quantitatively characterized considering both crack opening and crack length growth. Focusing crack opening, the evolution of this parameter (normalized considering the graphite nodule diameter) as a function of macroscopic deformation is shown in Fig. 7 (only about 33% of the investigated nodules are shown, in order to obtain a higher behaviour evidence). A threshold value of the macroscopic deformation is between 2.5 (the end of the elastic stage) and 5%: in this range, an irreversible damaging of graphite nodules begins to be evident (e.g. Figs 3c and 3d). Damage parameter, defined as crack opening /graphite nodule diameter, seems to be roughly linearly correlated with the macroscopic deformation.

Focusing damaging in ferritic matrix, plastic deformation seems to be more and more evident in the plastic deformation range (ε% higher than 2.5%): slip bands become more and more evident with the macroscopic deformation increase. Corresponding to very high deformation levels, cracks initiate and propagate (Fig.8). SEM fracture surface analysis confirms graphite spheroids damage, with the presence of graphite residuals inside holes. Fracture surface is also characterized by an evident cleavage of ferritic grains (Fig. 9).

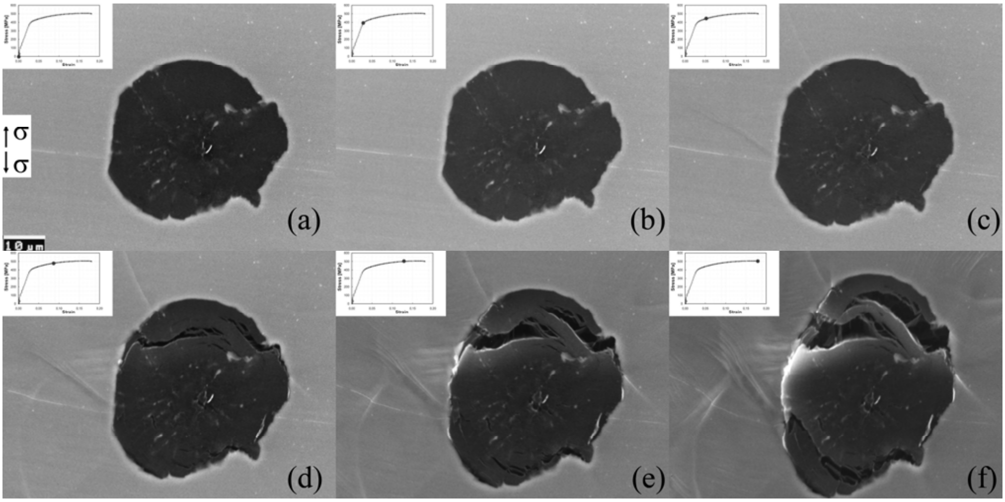

Fig. 3: EN GJS350-22 ductile cast iron (100% ferrite). SEM in situ surface analysis corresponding to the following σ [MPa]-ε% values: (a) 0–0%, (b) 400–2.5%, (c) 430–5%, (d) 470–7.5%, (e) 490–12.5% and (f) 500–17.5%.

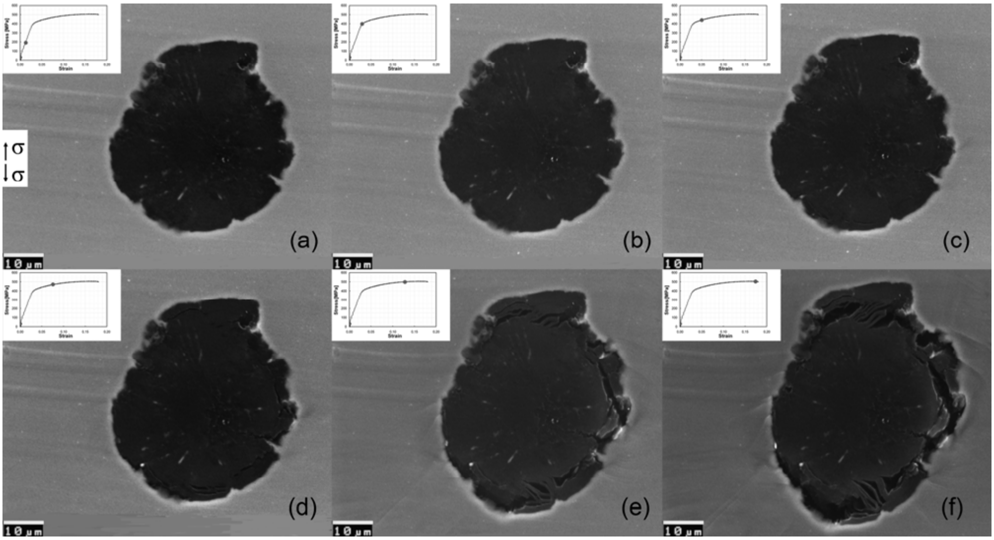

Fig. 4: EN GJS350-22 ductile cast iron (100% ferrite). SEM in situ surface analysis corresponding to the following σ [MPa]–ε% values: (a) 200–1%, (b) 400–2.5%, (c) 430–5%, (d) 470–7.5%, (e) 490–12.5% and (f) 500–17.5%.

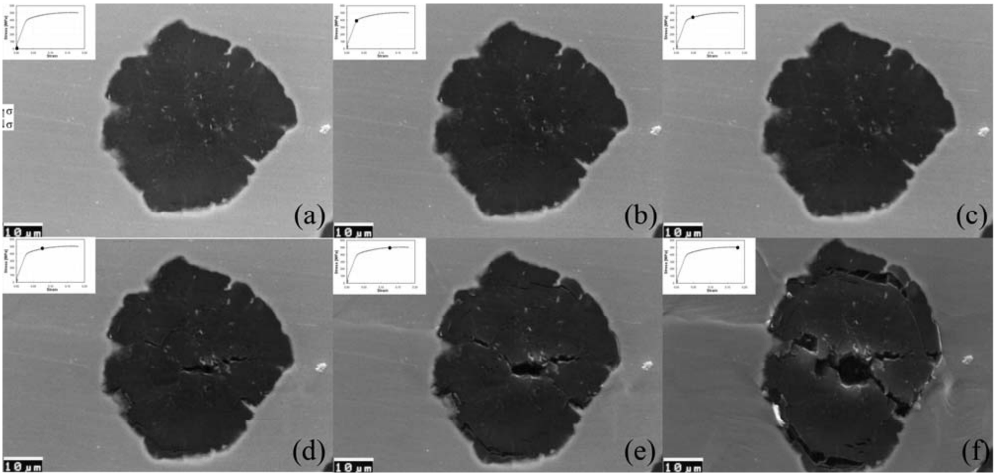

Fig. 5: EN GJS350-22 ductile cast iron (100% ferrite). SEM in situ surface analysis corresponding to the following σ [MPa]–ε % values: (a) 0–0%, (b) 400–2.5%, (c) 430–5%, (d) 470–7.5%, (e) 490–12.5% and (f) 500–17.5%

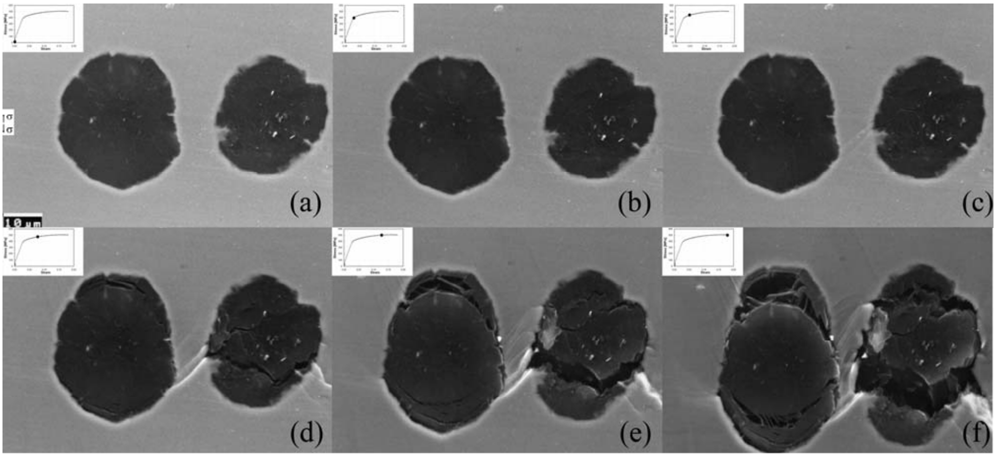

Fig. 6: EN GJS350-22 ductile cast iron (100% ferrite). SEM in situ surface analysis corresponding to the following σ [MPa]–ε % values: (a) 0–0%, (b) 400–2.5%, (c) 430–5%, (d) 470–7.5%, (e) 490–12.5% and (f) 500–17.5%.

Graphite elements in ductile irons are usually considered as voids with practically no strength [10], which decrease the load carrying area and cause stress concentration. According to this proposed graphite behaviour, cracks should initiate corresponding to the maximum stress conditions sites (in the matrix, just adjacent to sharp graphite tips). The effective damaging mechanism is quite different. Lower macroscopic ductile deformation levels correspond to graphite spheroids damage (as previously listed) and to a more and more slip bands generation. Higher macroscopic ductile deformation levels correspond to a more evident graphite elements damage and to crack initation and propagation in ferritic grains, with an evident ferritic grains cleavage.

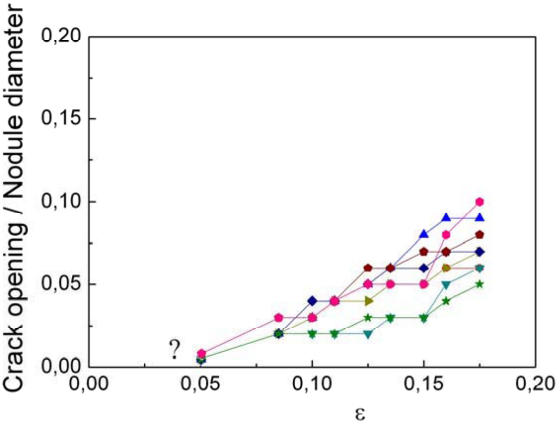

Fig. 7: EN GJS350-22 ductile cast iron (100% ferrite): crack opening/nodule diameter as a function of the macroscopic deformation.

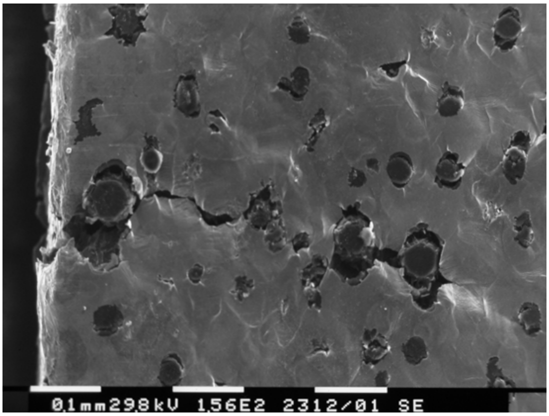

Fig. 8: EN GJS350-22 ductile cast iron (100% ferrite). SEM in situ surface analysis σ [MPa]-*ε* % values: 0–18%.

Conclusions

DCIs combine the good castability of gray irons and the toughness of steels. This is due to their peculiar graphite shape, obtained by means of a chemical composition control and not by means of extended annealing treatment of white irons as in malleable irons. DCIs are widely used in a number of applications, e.g. wheels, gears, crankshafts in cars and trucks, etc. They are characterized by a good combination of overall properties, depending on the matrix microstructure and graphite nodules morphology and distribution. DCIs main damage micromechanism is often identified as voids growth corresponding to graphite nodules and numerous studies provided analytical laws to describe growth of a single void, depending on the void geometries and matrix behavior: as a consequence, DCIs are often considered as porous materials, graphite nodules being considered as voids in an elastic–plastic matrix. Microcracks in graphite nodules were also experimentally observed, but their presence and evolution was considered as negligible. Damage main micromechanism was identified with graphite–matrix debonding, and all the other damaging micromechanisms were simply not considered.

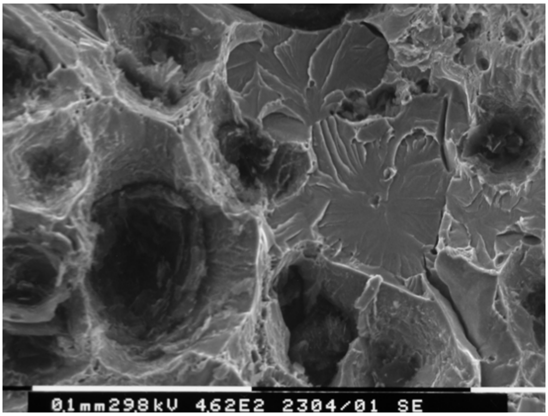

Fig. 9: EN GJS350-22 ductile cast iron (100% ferrite). SEM fracture surface analysis.

In this work, a ferritic DCI was considered: damaging micromechanisms were investigated by means of scanning electron microscope (SEM) "in situ" observation during tensile tests performed in air. Step by step tensile tests were performed and both graphite nodules and ferritic matrix damage evolution was focused.

Focusing graphite nodules, the following main damaging morphologies could be identified:

- An "onion-like" damage mechanism: nodule shield debonds from nodule core by means of a ductile mechanism; this mechanism is probably connected to a different mechanical behaviour between the nodule "core" (obtained directly from the melt) and the carbon shield (obtained by means of solid diffusion during cooling).
- Radial and transversal cracks initiation and propagation: this graphite element damage mechanism usually initiates corresponding to graphite elements with a reduced roundness; some radial cracks were also identified in nodule cores, probably corresponding to graphite solidification nucleation sites (e.g., non metallic inclusions like MgS or CaS);
- Interfacial microcracks at the graphite elements – matrix interface are only seldom observed, and their importance seems to be lower than other graphite elements damaging mechanisms.

Ferritic matrix damage is strongly connected to the increasing presence of slip bands and, corresponding to very high ductile deformation level, to crack initiation and propagation, up to specimen final rupture.

Finally, graphite nodules – ferritic matrix debonding is not the main damaging mechanism in ferritic DCI and the graphite nodules contribution to DCI mechanical behaviour is more complex.

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