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Graphite nodule morphology as an indicator of the local complex strain state in ductile cast iron

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ABSTRACT

Compression tests were carried out on ductile cast iron with different sample geometries in order to understand the influence of the stress triaxiality on the local strain. The tests were performed in dry friction conditions involving a complex local stress and strain state with a severe barrelling. The numerical simulation of the compression tests was achieved by using finite element analysis. Local strain was evaluated using microstructural quantifications. A relationship between the nodule strain, experimentally determined at different stress–strain stages, and the numerical simulation is proposed. The numerical predictions agree with the distribution of the experimental aspect ratio defined as the ratio between the major and minor axis of the graphite nodules. This study shows that the nodule strain is a good indicator of the total material strain at room temperature for different triaxiality states and complex strains. In addition, it was highlighted that graphite nodules cannot always be considered as ordinary voids during the plastic strain process.

1. Introduction

Ductile Cast Iron (DCI) is widely used in the automotive industry for different applications such as manifolds, crankshafts, wheels and gears, since it covers a large range of mechanical properties. Due to its particular microstructure, DCI is a natural metal matrix composite made of spherical graphite nodules embedded in a ferrous matrix. Ferritic DCI is a material characterized by good ductility (uniform deformation traditionally higher than 0.1 at room temperature in tensile tests conditions), tensile strength values typically around 700 MPa, equivalent to those of the low carbon steel, and good fatigue behaviour [1–3].

Many previous studies have investigated the strain behaviour and the workability of DCIs in order to improve their mechanical properties [4–8]. One of the main results of these studies is the necessity to deeply understand the deformation process of graphite nodules in order to optimize the properties of ductile iron in structural parts. However, few works were concerned by the link between local plastic states and microstructural deformation, with the objective to build microstructural tools for the control of the strain path during formability processes. Shi et al. [9] studied the strain ratio of graphite nodules, metal matrix and bulk DCI, during compression tests. The geometrical nodule aspect ratio was proposed as a suitable parameter permitting to predict the homogeneous strain of the material. More recently, Balos and Sidjanin [10] used the same parameter to investigate the evolution of the graphite nodule morphology during mechanical tests carried out at room temperature, on ferritic and pearlitic DCI. They observed that the strain nodules ratio between different phases depends on the bulk strain and not on the metal matrix microstructure. Sjögren et al. [11] compared the local strain of the graphite phase with the local strain of the compacted ductile iron matrix (pearlitic and ferritic) using digital image correlation during tensile tests. They noted that the strain is not homogeneous in the bulk material due to a graphitic phase more deformed than the ferritic one, itself more deformed than the pearlitic phase.

In addition, many previous works on the tensile and fatigue mechanical behaviours suggested that DCIs should be considered as porous materials with graphite nodules similar to voids in an elastic–plastic matrix [12–14]. This hypothesis holds true when damage occurs by debonding mechanisms between nodules and the metallic matrix. After this initiation stage, plasticity of the metallic matrix drives the overall strain behaviour of the material. Different studies [15,16] consider the continuous nucleation and the growth of damage at the interface matrix-graphite. Di Cocco et al. and Iacoviello et al. [17,18] observed the *in situ* damaging micromechanisms of DCI occurring during tensile tests by means of microtensile experiments performed in a scanning electron microscope. They highlighted new damage processes such as microcracks or onion like mechanisms, different from the usual debonding, depending on the matrix nature. This type of damage

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consists of internal debonding of graphite due to the difference of mechanical properties between the graphite core obtained directly from the melt and the carbon shield obtained by means of solid diffusion during cooling [19,20].

All these studies have investigated the influence of the graphite nodules on the bulk material strain in homogeneous mechanical loading conditions. However, the graphite behaviour depends on the mechanical loading and no experimental data is available in the literature concerning the role of local complex strain state on the deformation of the nodules. The main objective of this study is to link local geometric properties of nodules, such as aspect ratio, to the corresponding plastic strain level of the DCI. At this end, compression tests were carried out at room temperature with different sample geometries for distinct compression levels in order to create a gradient of stress triaxiality and a complex strain stage. Microstructural observations and measurements of nodule dimensions permitted us to follow their dimensional evolution. Moreover, these local experimental observations were compared to the results of the numerical simulation of compression tests of cast iron. The nodule aspect ratio was used as a parameter in order to compare the strain of the homogeneous bulk material numerically simulated with the local measurements experimentally done on nodules. Finally, the main results of this work are discussed in terms of local damage evolution and plastic straining of the graphite nodules.

2. Materials and methods

2.1. Material properties

The material used in this study is a ferritic (silicon, molybdenum) SiMo DCI. Its chemical composition is shown in Table 1. Microstructural features were studied thanks to a previously detailed methodology [21]. Nodule geometrical parameters (i.e. their volume fraction, their mean size diameter and their aspect ratio) were obtained thanks to a numerical treatment of surface images of polished samples using light microscopy and Scanning Electron Microscopy (SEM). Fig. 1a shows the SiMo ductile cast iron microstructure before chemical etching whereas Fig. 1b gives the corresponding microstructure after etching, which is made up of graphite nodules surrounded by ferritic grains. SEM observations combined with Energy Dispersive Spectrometry (EDS) enable us to obtain mapping measurements of addition elements. This highlighted that pearlite (about 10% vol.) is located close to rich molybdenum carbides.

Mean grain size and crystallographic texture were computed by Electron Back-Scattered Diffraction EBSD on electropolished samples. DCI exhibits a weak crystallographic texture. The corresponding maximal density expressed in multiples of a random distribution (m.r.d. units) is lower than two (Fig. 1c). Moreover, the dominant pole {001} lies parallel to the compression direction. Consequently, the mechanical behaviour of the DCI is supposed to be unaffected by its crystallographic texture.

Ferritic grain diameter follows a normal distribution with a mean value equal to 10 μm and a standard deviation of 4.4 μm (Fig. 2a). Nodule equivalent diameter and aspect ratio r, which corresponds to the ratio between the major and the minor axis lengths, were measured using a numerical treatment on the images of the sample polished surfaces. The mean nodule diameter is 16.8 μm with a standard deviation of 6.4 μm (Fig. 2b). Nodule aspect ratio follows a normal distribution with an average value of 1.23 and a standard deviation of 0.35 (Fig. 2c).

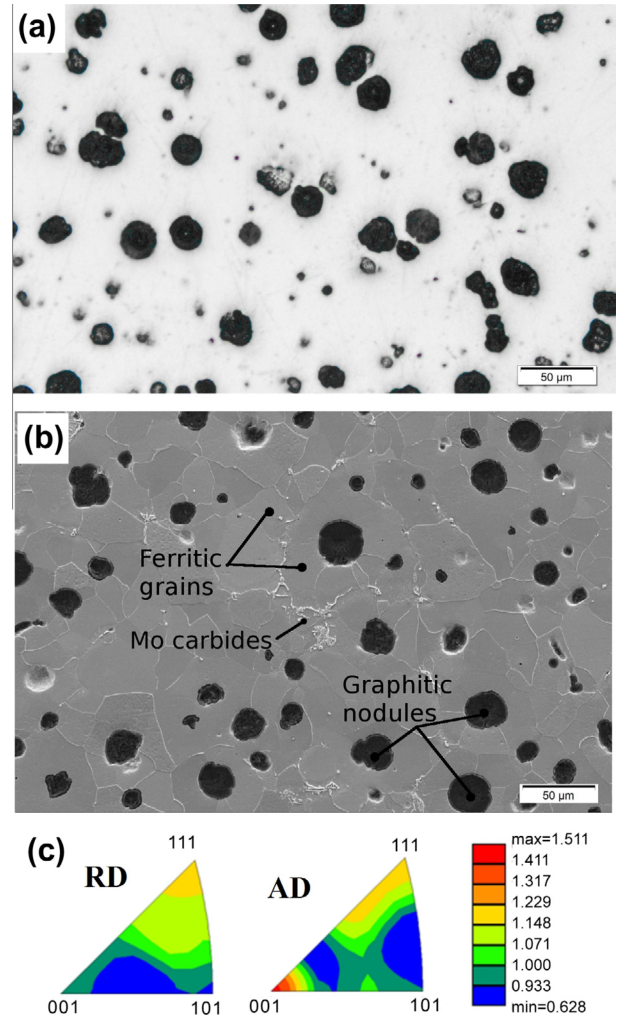

Fig. 1. Typical microstructure of DCI. (a) Before etching (light microscopy). (b) After etching (SEM observations). (c) Normalized {111},{001} and{011} inverse pole figures representing crystallographic texture of DCI (EBSD measurements, AD: axial direction, RD: radial direction).

2.2. Mechanical testing

Different cylindrical compression samples were tested (5 mm diameter) with *H/D* (height/diameter) ratios equal to 2, 1 and 0.5 respectively (Fig. 3a). Compression tests were carried out at constant strain rate value of 10^{-3} s^{-1}. Axial displacement was measured with a laser extensometer and the extensometer reference lines were placed close to the edges of the samples. Cylindrical specimens were deformed at different compression levels until breaking. Tests were performed in dry friction conditions

Table 1
Chemical composition of the ductile cast iron (in wt.%).

Si	C	S	Mg	Mn	Cr	Mo	Sn	Cu	P
4.240	3.000	0.005	0.028	0.220	0.070	0.610	0.009	0.020	0.020

Fe: balance.