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Microstructural study of the mechanical response of compacted graphite iron: An experimental and numerical approach

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ABSTRACT

Graphite is an important microstructural constituent in cast irons, which plays a key role in determining the material performance. This work aims at understanding the microstructural phenomena taking place in compacted graphite cast iron (CGI), and in particular the effect of the anisotropy of graphite particles on the microscale strain partitioning. To this end, an experimental–numerical approach is followed. First, in situ micro-tensile tests on CGI samples are carried out in the scanning electron microscope (SEM). From these tests, high resolution images of deforming graphite particles within CGI are obtained. These images are then used to calculate the strains within the graphite particles via the Global Digital Image Correlation (GDIC) procedure. To correct for the inherent SEM imaging artifacts the use of external reference frame is proposed. The results from the tests confirm the mechanical anisotropy of compacted graphite particles in cast irons. Next, the strain partitioning is studied numerically through a 2D microstructural model based on the SEM micrographs. Good qualitative agreement is found between the computed and measured strains within the graphite particles, validating the hypothesis on graphite mechanical anisotropy. Moreover, the numerical study reveals that graphite anisotropy has a high impact on the elasto-plastic response of the matrix material and the CGI as a whole.

1. Introduction

Cast irons belong to the group of ferrous alloys whose carbon content is higher than 2.14% in weight percentage (wt%). Nevertheless, in most cast irons it is close to 3 wt%. Besides carbon, other alloying elements like silicon, magnesium and copper are frequently added (Table 1). The high carbon content present in cast irons leads to the formation of graphite inclusions that give cast irons their characteristic microstructure composed of graphite particles embedded in a pearlitic and/or ferritic matrix. Depending on the chemical composition and processing conditions, *lamellar*, *vermicular* or *nodular* graphite inclusions appear. Accordingly, the cast irons are generally classified based on the morphology of the graphite inclusions such as *Flake or Lamellar Graphite Iron* (*FGI*), *Compacted or Vermicular Graphite Iron* (*CGI*) and *Spheroidal, Nodular or Ductile Graphite Iron* (*SGI*). While the graphite particles in SGI are mostly isolated graphite nodules, in FGI and CGI the graphite inclusions form a 3D interconnected network that plays a crucial role in determining the mechanical and thermal properties of the material. In particular, the interconnected graphite network together with graphite high thermal conductivity and low thermal expansion results in a material with better heat conduction properties and lower thermal expansion compared to most steels. Furthermore, the vermicular shaped graphite inclusions in CGI, as compared to the sharp lamellas present in FGI, make CGI a material with better mechanical properties than FGI.

The experimental findings in the literature on microstructural deformation mechanisms in cast irons [1–7] are mostly related to the role played by the interface and the graphite/matrix elastic mismatch in damage initiation and propagation. The influence of the graphite anisotropy on the microstructural mechanical response of cast irons has only been briefly addressed, i.e. only in relation to its role in crack initiation within the graphite particles [3]. In terms of microstructural modelling of the local response of nodular cast irons [1,8–10] or compacted graphite irons [11,12], the graphite has been generally considered as an isotropic material, whereby the values assigned to its elastic constants show high variability between different references.

In contrast to the frequently made modelling assumption on graphite isotropy, experimental observations of the structure of graphite particles within cast iron indicate that graphite inclusions present a layered structure with strong covalent bonds within the basal planes ("*a*" crystallographic direction) and weak van der Waals bonds between them ("*c*" crystallographic direction) [3,13–

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Table 1
Chemical composition (wt%) of the pearlitic CGI [19].

C	Ti	Cr	Mn	Cu	Sn	Pb	Si
3.60–3.90	<0.015	<0.10	0.15–0.40	0.75–0.95	0.06–0.10	<0.002	1.90

18]. This structure makes graphite a transversely isotropic material, mechanically strong in the "in-plane" direction and weak in the "out-of-plane" direction.

The crystallographic orientation of graphite within a given particle is determined by its morphology, which in turn is closely related to the particle growth mechanism. Lamellar graphite grows predominantly in the "*a*" crystallographic direction [13,17]. As a consequence, the basal planes are parallel to the lamella growth direction. In nodular graphite, conical graphite crystals grow in a radial pattern from the nucleus along the "*c*" direction [13,14,17,18]. Vermicular graphite presents a more complex growth pattern which alternates between the "*a*" and "*c*" directions [18]. Initially, close to the nucleus, vermicular particles grow in a similar way as nodular graphite. However, upon further growth the branches grow preferentially in the "*a*" direction as in lamellar graphite [17]. Clearly, the frequently made assumption of isotropic graphite inclusions is invalid, as shown in these observations.

This paper aims to study the graphite crystallographic anisotropy in vermicular graphite particles and its influence on CGI micromechanical behavior. In particular the following research question will be addressed:

- How important is the mechanical anisotropy for the distribution of strains and deformation in vermicular graphite particles?

To address this question, an experimental–numerical approach is followed to study the deformation of the graphite inclusions within CGI. First, in situ micro-tensile tests on CGI samples are carried out in a scanning electron microscope (SEM). From these tests, a sequence of high resolution images of the deforming graphite particles within CGI is obtained. These images are then used to calculate the strains within the graphite particles via an advanced Global Digital Image Correlation (GDIC) procedure to achieve reliable strain measurements at the scale of the graphite particles (10–50 μm). The method introduced here combines the use of reference grids on top of the sample together with a dedicated GDIC algorithm to correct for image artifacts and distortions often found in SEM. This is discussed in Section 2, followed by the experimental results in Section 3. The second part of the paper is dedicated to the development of 2D microstructural models to computationally evaluate the influence of graphite anisotropy on CGI's mechanical behavior. To this end, in Section 4.1 SEM micrographs are used to create 2D CGI microstructural models. Next, in Section 4.2 the computed strains within the graphite inclusions are compared to the experimentally measured strains. Then, in Section 4.3, a comparative analysis on the effect of the graphite anisotropy on the matrix response is performed by confronting the results of two models, one in which some graphite particles are considered anisotropic and one in which all the particles are assumed isotropic. Finally, the main conclusions are presented in Section 5.

2. Experimental procedure

2.1. Material and sample preparation

The material considered in this paper is a pearlitic CGI with a carbon content between 3.60 and 3.90 weight percentage (wt%). The detailed chemical composition of the material is specified in Table 1.

Dog-bone shaped samples were extracted by electrical discharge machining from the valve bridges of a newly produced truck engine cylinder head. The samples' cross section was 1 mm thick and 5 mm width, with a gauge length of 35 mm. Care was taken to develop a reproducible procedure to metallographically prepare the surface of the samples by successive grinding, polishing and fine polishing steps, in order to yield a scratch free surface. No etching was applied to avoid undesirable effects on the graphite/matrix interface.

Tensile tests were carried out using a Kammrath–Weiss microtensile stage. The samples were loaded up to fracture by applying a prescribed displacement at a rate of 1 μm/s. The micro-tensile stage was placed inside a FEI QUANTA 600 FEG scanning electron microscope (SEM). Four successful high resolution tests were performed. In each test, one graphite particle was preselected and monitored (in situ) during the loading. Three tests were used to study the particles with the principal axis (i.e. parallel to the particle growth direction) perpendicular to the loading direction, and one test was done on a particle with principal axis parallel to the loading direction. High resolution micrographs were obtained in the secondary electron (SE) mode at increasing global strain levels. Four to five micrographs were taken at each global strain level.

2.2. SEM based digital image correlation

Quantification of the local deformation of the graphite particles requires the use of a high resolution imaging system such as SEM. However, the use of SEM in combination with digital image correlation (DIC) to quantify the deformation of a microstructure can be problematic. Due to the inherent nature of the SEM imaging, image artifacts and distortions are frequently present, which are a particular concern at high magnifications and high resolutions [20–22]. This makes the use of DIC at the length scales required in this work challenging, especially when the strain resolution reflects the variations in local elastic properties in different directions. A more detailed account of the various challenges encountered in SEM with DIC and some related approaches to tackle them can be found in [20–22]. All these methods rely on averaging over multiple images to reduce the detrimental influence of SEM scanning artifacts.

Here, an alternative approach is followed which is based on the use of a reference grid surrounding a given region of interest (ROI) within the sample. The reference grid is placed on top of the sample. When the sample is deformed under loading, the reference grid moves with the sample, but remains undeformed. In this work, measurements are performed simultaneously at two length scales: the macroscopic scale of the tensile sample, and the microscopic scale of a graphite particle. Accordingly, two reference grids are used. This is illustrated in Fig. 1, where the two reference grids are shown. At the macroscopic level an aluminum mask is used as reference grid 1 to correct for the scanning artifacts at a "global" level (Fig. 1a and b). At the microscopic level, reference grid 2 is used to correct for the scanning artifacts when measuring at the graphite particle scale (Fig. 1c and d). Reference grid 2 is a 5 μm thin micromachined Al-1 wt% Cu plate [23], with holes of various sizes.

2.2.1. Image correlation procedure

As discussed in [24–26], in GDIC an image *g* taken in the current deformed configuration is correlated with an image *f* taken in the reference undeformed configuration to determine the unknown displacement field resulting from the deformation of the