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Modeling the elastic behavior of ductile cast iron including anisotropy in the graphite nodules

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ABSTRACT

This paper presents a micro-mechanical approach to model the intrinsic elastic anisotropy of the graphite particles in ductile iron. Contrary to most of the published works in the field, the constitutive behavior is directly derived on the basis of the nodule characteristic internal structure, composed of graphite platelets arranged into conical sectors. In this way, the large uncertainty traditionally associated with local mechanical measurements of micro-hardness is eliminated. The proposed anisotropic description is validated by simulating the macroscopic ductile iron elastic response by means of a 3D periodic unit cell model. In this respect, an explicit procedure to enforce both periodic displacement and periodic traction boundary conditions in ABAQUS is presented, and the importance of fulfilling the traction continuity conditions at the unit cell boundaries is discussed. It is shown that localized inelastic deformation is likely to develop for loading conditions which can still be considered as elastic at the macroscopic scale. The presence of a weak interface between the graphite and the matrix is also investigated, and it is found to affect the results to a limited extent only.

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1. Introduction

Among the multitude of high-performance metallic materials available today, ductile cast iron, also known as spheroidal graphite iron (SGI), is probably one of the very few boasting a positive growth rate on the market since its commercial introduction in 1948 (Ductile Iron Society, 2013). According to recent estimates, as many as 25% of the castings produced worldwide are made of SGI (*47th Census of World Casting Production*, 2013) and represent mainly small and medium sized heavily loaded parts with high demands for consistent quality for the automotive sector and very large industrial components with extreme demands for mechanical properties, particularly fatigue strength and fracture toughness (Tiedje, 2010).

From a metallurgical perspective, SGI may be classified as a ternary Fe-C-Si alloy (Labrecque and Gagne, 1998) whose properties to a large extent are controlled by chemical composition, cooling rate and heat treatment. The final microstructure may be naturally considered as composite (Grimvall, 1997 and Sjögren and Svensson, 2004), consisting of graphite nodules embedded in a continuous matrix which, in most engineering applications, may be either ferritic, pearlitic or a mixture of the two.

Due to its high technological importance, a number of papers have addressed the problem of modeling the mechanical behavior of SGI, particularly ductile fracture and fatigue. Nevertheless, the intrinsic material complexity has always posed severe challenges, and as recently pointed out by (Hütter et al., 2015) in a review article, much work is still needed to bridge the gap between microstructural features and global properties. Particularly, according to the former authors, a deeper understanding of the mechanical response of the single constituents at the micro scale is highly necessary.

Concerning this point, an important element, which has probably received much less consideration than necessary in the past, is the mechanical nature of the graphite particles. Several numerical investigations on the non-linear behavior of SGI during tensile testing published in the late ‘90 s ((Kuna and Sun, 1996; Brocks et al., 1996 and Zhang et al., 1999) among others) were based on the concept of a voided material model, meaning that the nodules were simply neglected in the analyses. This was motivated by their presumed “soft” nature and the early debonding from the matrix,

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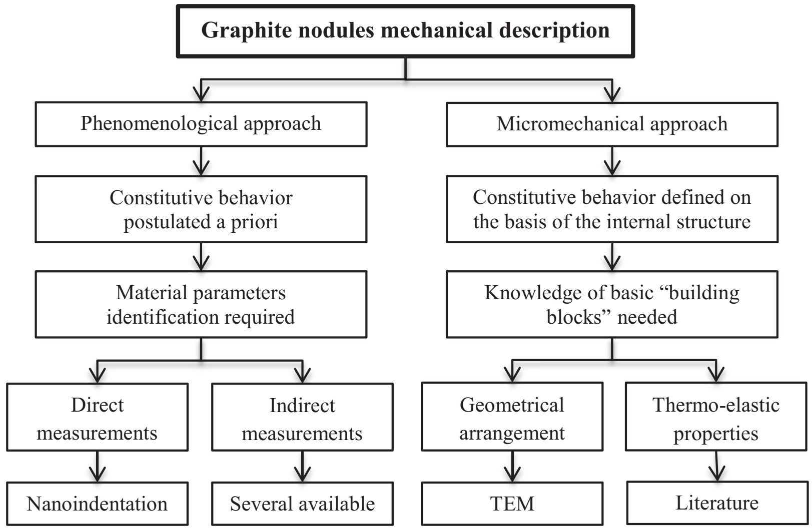

Fig. 1. Schematic of the two different approaches used to model the mechanical behavior of the graphite nodules.

often observed experimentally (Dong et al., 1997). It is quite clear, however, that this assumption may be reasonable at high values of the triaxiality ratio, but it cannot be justified under pure shear or in situations where the hydrostatic part of the stress tensor becomes negative. Several experimental facts point in this direction, as discussed in detail in (Andriollo et al., 2015a,b). Perhaps, the most striking evidence of this is that 1) at temperatures close to the eutectoid transformation, the nodules remain undeformed under heavy compressive deformation of SGI samples (Hervas et al., 2013) and 2) the low-cycle fatigue behavior with negative stress ratio is better reproduced by numerical models where nodules are treated as rigid spheres instead of voids (Rabold and Kuna, 2005). Hence, as loading scenarios for real SGI components usually involve complex combinations of tensile and compressive stresses (Shirani and Härkegård, 2011), the simplistic voided material assumption is likely inadequate.

On the other hand, including the graphite particles in the analysis is not trivial, primarily because of the lack of reliable data concerning their mechanical properties. The vast majority of authors who have tried to model the nodules' behavior have followed the phenomenological approach summarized in Fig. 1, assuming an isotropic linear elastic response. Unfortunately, the procedure suffers from two important shortcomings.

First of all, it is very hard, if not impossible, to perform a direct identification of the required material parameters. In fact, the only easy way to experimentally characterize the nodules is via nano-indentation (Oliver and Pharr, 1992). The method however, is quite disputable, as it relies on an exact isotropic elastic solution (Harding and Sneddon, 1945) whereas graphite is notoriously highly anisotropic at the local scale. Moreover, it was argued by (Bonora and Ruggiero, 2005) that the sharp indenter usually employed could simply separate the graphite layers without creating any elastic deformation at all. In light of these considerations, parameters identification based on indirect measurements, e.g. testing the stiffness of SGI at the macroscopic level, is sometimes preferred. In both cases, however, the phenomenological approach has proved to lead to large uncertainties, as confirmed by Table 1, which reports the nodules' isotropic elastic constants assumed by several researchers over the last 30 years.

The second important drawback is that the isotropy assumption cannot be justified using elastic bound theory analysis. In a recent work, (Andriollo and Hattel, 2016) determined an admissible domain for the Young's modulus and Poisson's ratio of the graphite particles by means of homogenization theory for polycrystalline materials. Using both analytical and numerical micromechanical techniques, the implications of adopting nodules' moduli within such admissible domain were investigated in relation to the effective elastic constants of a common grade of ductile iron. It was found that the predicted effective parameters never match the reference experimental values, no matter the choice of the admissible nodules' moduli. Furthermore, this important conclusion still holds when the influence of factors like weak interface bonding between the matrix and the graphite and local residual stresses arising during manufacturing is taken into account.

The limitations of the phenomenological approach discussed so far motivate the adoption of different strategies to model the nodules. As shown in Fig. 1, another possibility is to use a micromechanical approach, where the nodules' properties are obtained directly on the basis of their real internal structure. As previously mentioned, the latter is composed of graphite platelets arranged in a characteristic radial fashion (Theuwissen et al., 2012). As the moduli of the graphite hexagonal unit cell are known, the elastic response of the entire nodule can in principle be calculated without the need of any inverse analyses. To the authors' best knowledge, the only systematic work along this line was carried out by (Dryden and Purdy, 1989); in their analysis, however, a quite rough approximation of the platelets arrangement was made in order to solve the problem analytically, which was later found to generate unrealistic values for the macroscopic SGI elastic properties.

The aim of the present work is to extend the findings of the abovementioned authors by considering a more realistic description of the nodules' internal structure according to the most recent TEM investigations. More specifically, the observed subdivision of the graphite particles into conical sectors is taken into account. Validation of the proposed model is performed by calculating the effective elastic properties of a periodic SGI unit cell containing a single graphite nodule and comparing them with those of a well-known ferritic ductile iron grade. Due to the complexity of the underlying 3D geometry, the commercial software ABAQUS is used for the purpose. Within this context, a thorough discussion regarding the implementation of suitable boundary conditions is given, motivating the importance of prescribing both periodic displacements and tractions along the cell boundaries.

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