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Determination of effective elastic properties of ferritic ductile cast iron by computational homogenization, micrographs and microindentation tests

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ABSTRACT

A comprehensive procedure for the prediction of the elastic behavior of ferritic ductile iron by means of multiscale analysis is introduced in this work. The procedure combines computational procedures for the homogenization analysis, micrographic analysis to retrieve the geometries for the finite element analysis, and microindentation tests to assess the elastic behaviors of the different phases of the microstructure. The size of the representative volume element (RVE) is assessed in terms of geometrical descriptors of the microstructure (graphite fraction and nodule count and size) and the invariance and isotropy of the homogenized elastic responses. The RVE is sized to contain at least 50 nodules, and it results from 100× micrographs. The results for the homogenized values for the Young's modulus and the Poisson's ratio are found in excellent agreement to the data retrieved from tensile tests, values reported in the bibliography and analytical formulas available in the literature. The proposed procedure can be easily extended to the characterization of cast irons with more complex microstructures.

1. Introduction

Cast irons are materials consisting in a continuous metal matrix with disperse graphite and/or carbide inclusions. Their properties are determined by their microstructures, which are the result of the solidification process and the subsequent heat treatments. Graphite is the stable form of pure carbon in cast iron. The shape, size and spatial arrangement of graphite in the microstructure, which can range from flakes (gray irons) to spheroids (ductile iron), dramatically affects the mechanical properties of cast irons. The graphite flakes provide excellent damping characteristics to gray irons, but they also act as stress raisers, which cause localized plastic flow at low stresses that conducts to fragile failure. In turn, the graphite nodules, which act as crack arresters, are responsible for the excellent mechanical performance of ductile cast irons (Warda, 1990).

Ductile irons (DI) allow for a wide range of mechanical properties via microstructure control. Because of their good mechanical performance and relatively low cost when compared to steels, ductile cast irons are increasingly applied in the construction of high stressed parts for machines and vehicles. DIs are labeled based on the nature of their matrices: ferritic, pearlitic, martensitic, austempered and austenitic among others. Ferritic DI (FDI) is usually used to replace low-carbon steel when ductility and good impact properties are required in marine applications, valves, fittings, truck and agricultural implements and automotive steering knuckles. FDI is typically obtained by an annealing heat treatment consisting of an austenitizing stage followed by a slow cooling down (Warda, 1990; Labrecque and Cagne, 1998).

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During the solidification process of DI, graphite and austenite nucleate independently into the liquid, with the austenite growing dendritically. As the solidification process advances, the austenite dendrites trap the surrounding nodules. Further growth of the graphite nodules takes place by carbon diffusion from the liquid to the nodules through the austenite envelope. Consequently, one dendrite contains several nodules. The resulting solidification structure is formed by multinodular solidification units commonly called eutectic cells, which are separated by regions called cell boundaries. The first to freeze zones, coincident with the axes and arms of the austenite dendrites, are usually named FTF. As the solid phases grow and collide with neighboring growing units, the last portions of remaining melt locate between them, and are referred to as the Last to Freeze zones (LTF) (Rivera et al., 2002, 1995). The solidification structure can be revealed from the microsegregation patterns of the alloy elements. In particular, elements dissolved substitutionally in austenite and ferrite, such as Si and Mn, have low diffusivity in the solid phase, so their segregation patterns originated during the solidification will change very little during cooling to room temperature and with subsequent heat treatments. In this context, the microsegregations can be measured qualitatively by using a number of techniques, such as microanalysis (Boeri and Weinberg, 1993; Rivera et al., 1988; Kostyleva et al., 1992) or metallographic techniques (Motz, 1988; Zhou et al., 1993). The effectiveness of several metallographic techniques were evaluated by Rivera et al. (1995), who applied a color reagent sensitive to microsegregation that provides the best results to reveal the solidification structure of FDI. Fig. 1 depicts an FDI micrograph after color etching where the graphite nodules, FTF and LTFs are marked. Given the fact that LTF zones solidify at the end of the process, certain alloy elements and impurities may diffuse and concentrate or be depleted in these zones. In addition, the natural volume change associated to solidification can induce the formation of small shrinkage cavities at the LTF (Rivera et al., 1995, 1999).

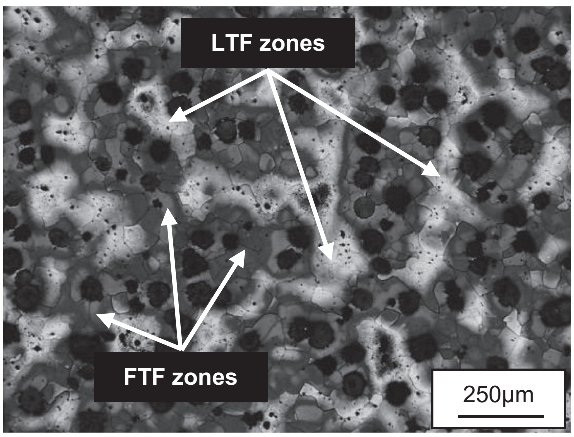

Fig. 1. FDI micrograph after color etching: spheroidal graphite nodules (black), FTF zones (dark zones) and LTF zones (bright zones).

The characterization of the FDI microstructure needs of geometrical and material-behavior constitutive data. The geometrical description is typically given in terms of graphite volume fraction, nodularity (a measure of the nodule sphericity) and nodular count (the number of nodules per unit area). In general, higher nodular counts and nodularities promote better mechanical properties (Burditt, 1992; http://www.ductile.org, 0000). In what respects to the material-behavior constitutive data, the usual assumption is to assimilate the matrix as homogeneous (Bonora and Ruggiero, 2005; Ghosh and Moorthy, 1995; Carazo et al., 2014; Hollister and Kikuchi, 1994; Hashin, 1983; Ortiz et al., 2001a; Basso et al., 2009; Kosteski et al., 2011; Ortiz et al., 2001b). However, the experimental evidence shows that the matrix presents a high degree of heterogeneity (see Fig. 1). The assessment of the associated heterogeneity in the mechanical properties needs experimental analysis at the microstructural level.

Computational micromechanics provides valuable tools to help to the better understanding of DI mechanical behavior. Finite, boundary and discrete element methods have been used to study the DI effective elastic response (Bonora and Ruggiero, 2005; Carazo et al., 2014) fatigue crack propagation (Ortiz et al., 2001a) and fracture (Bonora and Ruggiero, 2005; Basso et al., 2009; Kosteski et al., 2011). The hypotheses used in the geometrical description of the microstructure play a key role point when dealing with computational models. There are three approaches to account for the size and spatial distribution of the nodules: they are assumed to be of one size and periodically located (Bonora and Ruggiero, 2005), they are artificially generated by means of computer algorithms (Ortiz et al., 2001a; Basso et al., 2009; Kosteski et al., 2011; Ortiz et al., 2001b) or they are directly extracted from actual micrographs (Carazo et al., 2014). Analysis based on periodic microstructures are suitable to elaborate qualitative descriptions of the material behavior, but as it has been shown by Kosteski et al. (2011), they may conduct to erroneous results, especially when non-linear phenomena are involved. The simulations of non-periodic microstructures are based on homogenization analyses of Representative Volume Elements (RVE) (Hollister and Kikuchi, 1994; Zohdi and Wriggers, 2000). Among the various definitions available in the literature (Hashin, 1983; Willis, 2002; Kanit et al., 2003), the RVE is assimilated in this work to the minimum volume of material whose behavior is equivalent to that of a volume of a homogeneous fictitious material.

The present work is focused in developing a comprehensive procedure for the prediction of the elastic behavior of FDI. The procedure is based on the computational asymptotic homogenization of RVEs. The geometry of the RVEs is taken from actual micrographs, as this procedure offers a better chance to simulate more complex matrix microstructures and graphite morphologies and distributions, and, very importantly, to contemplate future simulations of nonlinear phenomena that demand detailed information about the microstructure. The non-homogeneity in the mechanical properties of the different microstructural phases is experimentally assessed by means of