Mechanics of Materials 96 (2016) 138–150

Contents lists available at ScienceDirect

Mechanics of Materials

journal homepage: www.elsevier.com/locate/mechmat

On the isotropic elastic constants of graphite nodules in ductile cast iron: Analytical and numerical micromechanical investigations

Tito Andriollo*, Jesper Hattel

Department of Mechanical Engineering, Technical University of Denmark, DK-2800 Kgs., Lyngby, Denmark

ARTICLE INFO

Article history:
Received 29 June 2015
Revised 7 January 2016
Available online 23 February 2016

Keywords:
Micromechanics
Ductile cast iron
Spheroidal graphite iron
Graphite nodules
Isotropic effective elastic moduli

ABSTRACT

A comprehensive description of the mechanical behavior of nodules in ductile iron is still missing in the published literature. Nevertheless, experimental evidence exists for the importance of such graphite particles during macroscopic material deformation, especially under compressive loading. In the present paper, the nodules' elastic properties are thoroughly investigated by means of both analytical and numerical techniques. The analysis takes into account the influence of several non-linear phenomena, as local residual stresses arising during solid-state cooling, interface debonding and limited particle strength. It is shown that if the nodule internal structure is considered, the traditional isotropy assumption leads to the definition of a domain of admissible values for the effective elastic constants. However, micromechanical calculations indicate that values within the domain do not provide mesoscopic moduli in agreement with Young's modulus and Poisson's ratio recorded for common ferritic ductile iron grades. This suggests that graphite nodules may not be considered isotropic at the microscopic scale, at least from a mechanical viewpoint.

1. Introduction

Since its commercial introduction in 1948, ductile cast iron, also known as spheroidal graphite iron (SGI), has constantly found new fields of application, ranging from the automotive sector to the wind power industry. Nowadays, 25% of the castings produced worldwide are made of SGI (47th Census of World Casting Production, 2013). The main reason behind this enormous success is the unique combination of castability, high ductility and strength such material can offer, along with lower prices compared to traditional low carbon steels (Ductile Iron Society, 2013). Examples of typical modern SGI castings are small and medium sized heavily loaded parts with high demands for consistent quality for the automotive industry and very large industrial components with extreme demands for mechanical properties, particularly fatigue strength and fracture toughness (Tiedje, 2010).

From a metallurgical viewpoint, SGI is a ternary Fe-C-Si alloy 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), 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 (American Foundrymen's Society, 1992). Extensive experimental investigations carried out in the last 60 years have provided qualitative knowledge of the effects of the most important microstructural parameters on the overall mechanical properties of SGI (Labrecque and Gagne, 1998). Nevertheless, a comprehensive quantitative description has always been challenged by the intrinsic material complexity, and much work remains to be done to cast light on

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* Corresponding author. Tel.: +4545254722.
E-mail addresses: titoan@mek.dtu.dk (T. Andriollo), jhat@mek.dtu.dk (J. Hattel).

http://dx.doi.org/10.1016/j.mechmat.2016.02.007

Nomenclature

E_{ij}	volume average of total strain tensor
Σ_{ij}	volume average of the stress tensor
ε_{ij}^{tot}, ε_{ij}^{e}, ε_{ij}^{p}	total, elastic, plastic strain tensor
σ_{ij}	stress tensor
s_{ij}	deviatoric part of the stress tensor
δ_{ij}	Kronecker delta
σ_e	equivalent Von Mises stress
σ_y, σ_y^0	Actual, initial yield stress
E	Young's modulus
ν	Poisson's ratio
K	bulk modulus
G	shear modulus
R_v	triaxiality function
f	yield function
D	Damage variable
S, s	Lemaitre's damage evolution parameters
Y	energy release rate
k, n	isotropic hardening parameters
p	equivalent Von Mises plastic strain
p_{crit}	critical effective plastic strain for damage evolution
r	hardening variable
α	thermal expansion coefficient
λ	plastic multiplier

the microscopic features which determine the mechanical constitutive behavior of SGI at the macroscopic scale.

In particular, the role of the individual graphite nodules is not fully understood yet. Probably, the main reason is that the only quantitative information available regarding their mechanical properties comes from nano-indentation tests performed according to the Oliver–Pharr method (Oliver and Pharr, 1992), which have provided values for the nodules Young's modulus in the range 15–28 GPa (Dierickx et al., 1996; Pradhan et al., 2009; Fernandino et al., 2015). The validity of such measurements is in any case disputable as (1) a priori values for Poisson's ratio must be assumed and (2) graphite nodules are not isotropic at all at the nanoscale (Miao et al., 1990; Miao et al., 1994), meaning that the concept of indentation Young's modulus loses its significance.

Often, in micromechanical analyses graphite nodules are simply regarded as voids in consideration of the above-mentioned presumed negligible stiffness and the weak bonding with the surrounding matrix. It must be emphasized that this last assumption is controversial too, as it is usually based on microscopy observations of early interface debonding for nodules sitting on the surface of tensile test specimens (Dong et al., 1997). As correctly pointed out in (Liu et al., 2002), the stress state around nodules located in the bulk is likely to be different, due to the material inhomogeneity, therefore it seems not possible to conclude that interface debonding always occurs, independently of the real local loading conditions.

Table 1
Micromechanical modeling of the SGI elastic response: assumed values for the nodules' isotropic elastic moduli.

Year	Authors	E_g (GPa)	ν_g
1980	Speich et al. (1980)	8.5	0.29
1992	Era et al. (1992)	303	Not specified
1997	Boccaccini (1997)	8.5	0.2
1998	Pundale et al. (1998)	0 (void)	0 (void)
2002	Cooper et al. (2002)	8.5	0.2
2003	Gaudig et al. (2003)	4.17	0.2225
2004	Sjögren and Svensson (2004)	*	Not available
2005	Bonora and Ruggiero (2005)	300-375	Not specified
2005	Collini and Nicoletto (2005)	15	0.3
2006	Nicoletto et al. (2006)	15	0.3
2014	Carazo et al. (2014)	*	0.2225
2015	Fernandino et al. (2015)	15	0.28

* $E_g = 0.173 \cdot Nodularity + 18.9 \rightarrow 36.2$ GPa for 100% nodularity.

As a matter of fact, there are clear indications pointing towards the mechanical importance of graphite nodules in SGI:

- First of all, low-cycle fatigue behavior with $R = -1$ is better reproduced by numerical models where nodules are treated as rigid spheres instead of voids (Rabold and Kuna, 2005). At the same time, it has been proved that fatigue crack propagation cannot be modeled within the classical linear elastic fracture mechanics framework (Berdin et al., 2001); this might be related to the fact that, according to the imposed stress intensity factor, different competing damage mechanisms are active in the matrix and / or in the nodules (Di Cocco et al., 2013).
- Secondly, tensile stress-strain curves for SGI are never linear, even at very low stress levels, due to immediate onset of plasticity (Sjögren and Svensson, 2005; Kohout, 2001). This can hardly be justified with a simple "voided matrix" model, as finite element calculations for the stress concentration factor corresponding to cavities of the shapes typical of real nodules have provided the maximum value of 5.39 (Dorazil, 1991).
- Thirdly, tensile and compression tests of SGI samples conducted at different temperatures (up to 800 °C) have highlighted large differences in the deformed nodule shapes (Hervas et al., 2013): if the graphite stiffness and strength were negligible compared to the matrix in the entire range of temperatures considered, the nodules should always deform in the same manner.

In light of these facts, it is clear that a thorough and complete understanding of the SGI mechanical behavior can only be achieved if accurate information on the nodules constitutive properties is available. This requirement is particularly important if non-linear phenomena like plastic deformation and fatigue are to be investigated, or the residual stresses arising during the manufacturing process are to be calculated. As previously mentioned, however, very little has been published in the literature concerning this issue, and even the basic elastic properties of the nodules are far from being firmly established. This uncertainty may be better appreciated by looking at Tables 1 and 2, which report the nodules' isotropic elastic constants