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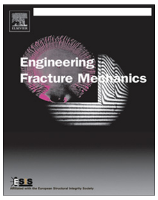

Micromechanisms of fracture in nodular cast iron: From experimental findings towards modeling strategies – A review

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ABSTRACT

This article presents an overview on modeling of micromechanical failure processes in nodular cast iron, a material used for many engineering applications. Depending on the loading conditions, different micromechanisms are responsible for damage and failure of nodular cast iron. The scope of this article is to derive a connection between experimental findings and simulation approaches for those different micromechanisms. Based on a review of experimental studies, the models are classified by several criteria into different modeling strategies. The main findings achieved for homogeneous stress states as well as for fracture and machining simulations are summarized and compared.

1. Introduction

Nodular cast iron[1] (NCI), also known as spheroidal graphite cast iron, is a carbon-rich iron alloy. Due to the high carbon content, graphite is found as particles on the microstructure level embedded into the metallic matrix. The term "nodular" refers to the shape of the graphite particles which is achieved by certain alloying elements like magnesium. Compared to classical gray cast iron with lamellar graphite, the nodular particle shape increases strength and toughness becoming comparable to many grades of steel. In addition, the cost-effective casting production allows a high design flexibility which is why nodular cast iron is widely used in industry, e.g. for gearboxes, crankshafts, pipes or nuclear storage and transportation casks.

The nodular graphite particles have a volume fraction between 7% and 15% and exhibit typically a diameter d_G in the range between 10 μm and 150 μm. They thus constitute strong heterogeneities in the microstructure affecting the macroscopic mechanical properties. Size, (deviations from the spherical) shape and distribution of graphite particles and the microstructure of the metallic matrix depend on temperature evolution during the casting process and possible subsequent heat treatments. Especially in thick-walled casted components the local temperature evolutions at the surface and in the center can differ considerably resulting in locally different microstructures and thus in locally varying mechanical properties.

Of course, then the question arises whether the local strength or toughness is sufficient to sustain the local loading conditions – or other the way round: Which microstructure has to be adjusted by (additional) heat treatments to make the component resist the local loading conditions? Answering these questions requires that a relation between microstructure and macroscopic mechanical properties can be drawn. This relation has been subject of both experimental and computational

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[1] Due to its mechanical properties nodular cast iron is also known as "ductile cast iron (DCI)". However, in order to avoid confusion with the damage mechanisms which will be discussed below, this term is omitted here.

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Nomenclature

DBT	ductile–brittle transition
NCI	nodular cast iron
TMF	thermomechanical fatigue
Δa	crack growth
f	shape factor
f_0	initial void volume fraction
J_c	fracture toughness
N	hardening exponent
$R_{p0.2}$	0.2% proof stress
T	stress triaxiality
λ	mean distance of graphite particles
σ_0	initial yield stress

investigations. The latter approach becomes more and more powerful with increasing computing power. Furthermore, NCI is an ideal material for this approach since the geometry of the microstructure can be easily determined by optical imaging and, as mentioned before, can be influenced specifically. That is why the present paper aims in providing a review on the current state of the art of the modeling of micromechanics of NCI pointing out the specifics of this material. Reviews on the applications and properties of NCI were published on occasion of 50 years of applications of NCI [71] and from German [10] and Japanese points of view [64]. A review on fracture testing of cast iron materials was given recently [97]. Reviews on the modeling of other engineering metals, typically steels and light-weight alloys, can be found elsewhere [17,96,117].

The outline of the present paper is as follows: In Section 2 some experimental results are reviewed briefly as they are necessary for an accurate modeling, before in Section 3 the available models are classified according to several criteria. Then, the classes of models are discussed in Sections 4 and 5 before we close with a summary and outlook.

2. Experimental characterization

2.1. Classification

The classification of NCI is defined in the standards EN-1563 [34] and ASTM A536 [5]. In both systems the grade code number is related to ultimate strength (MPa resp. ksi) and percent elongation at fracture. Both quantities depend on the microstructure of the metallic matrix and on the shape of the graphite particles. The matrix material can have a ferritic, pearlitic or austenitic structure or intermediate stages depending on the chemical composition of the matrix and on the heat treatment as shown in Fig. 1. In ferritic–pearlitic NCIs, a so-called "bulls eye" structures of ferrite can be found around the graphite particles, see Fig. 1b. By additional heat treatment the matrix material can be transformed into bainite consisting of needle shaped ferrite and austenite. This material is known as austempered ductile iron (ADI).

2.2. Stereology of NCI microstructures

In order to quantify the influence of the microstructure on the properties of NCI, one needs to define corresponding geometric measures of the statistical microstructure of NCI. Basic geometric quantities of NCI are the relative number of graphite particles (2D: N_A the mean number per unit area, 3D: N_V the mean number per unit volume), graphite volume fraction f_0 and a mean distance λ between centers of neighboring graphite particles These quantities can be obtained by statistical evaluation of 2D images from micrographs or from 3D images. The probably most prominent stereological method is closely related to the solution of Wicksell's corpuscle problem, namely the stereological estimation of the diameter distribution function of the spheres from the diameter distribution function of the section circles observed in a metallographic cross section [84,92]. A further problem is the characterization of the 3D arrangement of the graphite particles, which can be expressed in terms of the pair correlation function of the spheres' centers. A stereological method of estimating the pair correlation function of the spheres' centers from the pair correlation function of the section circles is presented in [48].

However, for practical applications it is usually not necessary to determine the complete distribution and correlation functions. Rather, it is desirable to establish links between mechanical properties of NCI and mean measures of its microstructure like the above-mentioned λ, f_0, N_A and N_V. The latter three quantities are related to each other by

$$f_0 = N_V \overline{V}, \quad f_A = f_0, \quad N_A = 2\overline{R} N_V, \quad \overline{V} = \alpha_V (2\overline{R})^3. \tag{1}$$

Therein, $\overline{R}$ and $\overline{V}$ denote the mean values of the particle radii and volumes, respectively. Furthermore, f_A is the area fraction of the graphite particles in a micrograph. Remarkably, f_A equals the volume fraction f_0 independent of the particular distribution of radii. The factor α_V accounts for the fact that the mean of the cubed diameter of the particles differs in general from