International Journal of Solids and Structures 87 (2016) 102–109

Contents lists available at ScienceDirect

International Journal of Solids and Structures

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

Computational assessment of the microstructure-dependent plasticity of lamellar gray cast iron—Part III: A new yield function derived from microstructure-based models

M. Metzger[a,b,*], T. Seifert[a]

[a] Offenburg University of Applied Sciences, Badstraße 24, 77652 Offenburg, Germany
[b] Fraunhofer Institute for Mechanics of Materials IWM, Wöhlerstraße 11, Freiburg 79108, Germany

ARTICLE INFO

Article history:
Received 20 May 2015
Revised 4 January 2016
Available online 23 February 2016

Keywords:
Gray cast iron
Microstructure
Micromechanics
Continuum model
Yield function

ABSTRACT

A new yield function for lamellar gray cast iron materials is proposed. The new model is able to describe the results of recently performed microstructure-based finite-element computations that resolve the three dimensional yield surface of three different gray cast irons. The yield function requires only the yield stress in tension and compression of the respective material as model parameters. Furthermore, the algorithmic formulation of the new model is assessed for numerical robustness and efficiency.

1. Introduction

This paper focuses on the derivation of a continuum model that describes the initial multiaxial yield behavior of the gray cast iron materials GJL-150, GJL-250 and GJL-350. The derivation is based on recent works where, volume elements (VE) including the real microstructure of these materials were reconstructed by means of the serial sectioning method and the obtained VEs were analyzed with the finite-element method (FEM) under uniaxial loading beyond yield, see Metzger and Seifert (2015a). The Fig. 1(a)–(c) illustrate the reconstructed VEs of the materials GJL-150, GJL-250, GJL-350. The added numbers in the notation correspond to the desired uniaxial tensile strength at room temperature in MPa. The pearlitic–ferritic metallic matrix is visualized brightly, the graphite inclusions are dark. In the finite-element model, the graphite inclusions are modeled with a volumetric strain state dependent Young's modulus E_G with a low value in tension to account for the separation between matrix and graphite and an experimentally measured limit value under volumetric compressive strains. The Fig. 1(d)–(f) show the results of the uniaxial tension and compression tests and of the finite-element analysis. The stress-inelastic strain curves that are used to describe the hardening of the metallic matrix are shown as well. The labeling *X*-, *Y*- and *Z*-direction corresponds to the direction in that the respective outer surfaces of the VEs are displaced.

Investigations under bi- and triaxial loading beyond macroscopic yield is investigated in Metzger and Seifert (2015b). In order to evaluate the yield stress in the VEs a definition for yielding is required that is somewhat arbitrarily. The onset of yielding can be defined by means of e.g. the inelastic equivalent strain state or, as done in this work, by the volume average of the locally varying inelastic work $\langle w^{\text{in}}\rangle = \langle \int_t \sigma_{\text{ij}}\dot{\epsilon}^{\text{in}}_{\text{ij}} dt\rangle$ that is directly available from the finite-element analysis.

The obtained yield surfaces are compared to four continuum models which, among others, are used in the literature to describe the inelastic behavior of gray cast iron with lamellar shaped graphite inclusions. A modified yield function for the model of Gurson (1975); 1977) due to Tvergaard (1981) and an extension that takes micro-cracking and/or decohesion between inclusions and the surrounding matrix into account by means of a stress driven nucleation law (Argon et al., 1975) is considered. Besides that the model of Josefson and Hjelm (1992), Hjelm (1994) and Josefson et al. (1995) that describes the plasticity of gray cast iron by two different yield functions is investigated as well. In contrast these two models, the model of Altenbach and Tushtev (2001) takes the Lode angle θ into account in the proposed yield function. This is also the case in the model that is available in the finite-element software ABAQUS, however, in contrast to the other three

* Corresponding author at: Fraunhofer Institute for Mechanics of Materials IWM, Wöhlerstraße 11, 79108 Freiburg, Germany. Tel.: +49 7615142470; fax: +49 7615142510.
E-mail address: mario.metzger@hs-offenburg.de, mario.metzger@iwm.fraunhofer.de, metz@iwm.fhg.de (M. Metzger).

http://dx.doi.org/10.1016/j.ijsolstr.2016.02.027

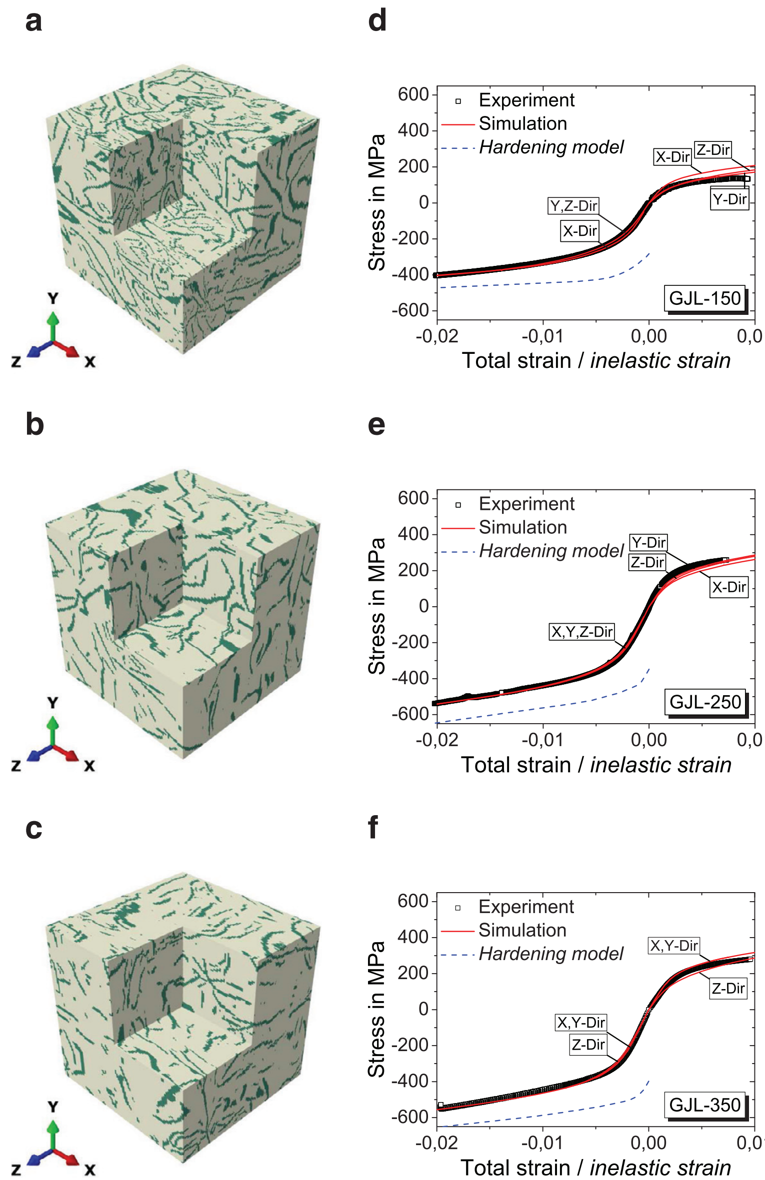

Fig. 1. Reconstructed VEs of Metzger and Seifert (2015a): (a) GJL-150, (b) GJL-250, (c) GJL-350, stress–strain curves: (d) GJL-150, (e) GJL-250, (f) GJL-350.

models the flow rule is not associated with the yield function under hydrostatic tensile stresses. It was found that none of the models is able to describe all features of the macroscopic yield surfaces obtained with the microstructure-based finite-element models, namely pressure-dependent yielding in hydrostatic tension and compression as well as the dependence of the Lode angle that changes with the pressure state.

Hence, it is the aim of this paper to derive a new yield function that agrees qualitatively and quantitatively better with the numerically resolved yield surfaces. Fig. 2 shows the respective yield surfaces in p–q space of the microstructure-based VEs.

p is the hydrostatic pressure and q the von Mises equivalent stress. The pearlitic–ferritic metallic matrix of the VEs is visualized brightly, the graphite inclusions are darker. The illustrated yield lines correspond to the average value of stresses obtained with the microstructure-based models at an equal Lode angle θ. The red points correspond to the average uniaxial yield stress in tension and compression that are obtained after loading in X, Y and Z direction. The green triangles belong to the yield stress for a volumetric strain state in tension and compression, respectively. The analyses show that the investigated materials are not only pressure-sensitive but do also depend on Lode's angle. At an equal pressure state p and $p > \sigma_{\mathrm{YC}}/3$ the macroscopic, numerically homogenized von Mises stress at yield is larger for $\theta = 60^\circ$ than for $\theta = 0^\circ$ and is observed the other way around for $p < \sigma_{\mathrm{YC}}/3$. σ_{YC} is the uniaxial macroscopic yield stress in compression computed by the volume average over the locally varying Cauchy stress tensor $\boldsymbol{\sigma}$, see Hill (1972). Subsequently, σ_{YT} refers to the numerically homogenized uniaxial macroscopic yield stress in tension.

Models that include pressure-sensitive yielding and also often the dependence on Lode's angle are used in the literature for different kind of materials like e.g. concretes, metallic powders or porous metals. The yield functions are rather complex and undesired effects like the loss of convexity might arise (see e.g. the model presented in Hjelm (1994) or the ABAQUS/Standard gray cast iron implementation). Furthermore, 'false elastic domains' as discussed in Brannon and Leelavanichkul (2010) or even undefined regions prevent the application of commonly used return mapping schemes and require additional effort as it is discussed in Stupkiewicz et al. (2014). Therefore, the yield function derived in