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Computational assessment of the microstructure-dependent plasticity of lamellar gray cast iron – Part II: initial yield surfaces and directions

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ABSTRACT

In this paper, the initial multiaxial yield behavior of three different gray cast iron materials with lamellar shaped graphite inclusions is numerically investigated by means of the finite-element method. Therefore, volume elements including the real microstructure of the materials are loaded bi- and triaxially beyond macroscopic yield. The shape of the obtained yield surfaces are compared to the surfaces of four continuum models which, amongst others, are proposed in literature to describe the inelastic behavior of gray cast iron with lamellar shaped graphite inclusions. It is found that the presented continuum models and the macroscopic yield surfaces obtained with microstructure-based finite-element models deviate. Furthermore, the initial inelastic flow direction is computed at the onset of macroscopic yielding. The analysis show that the inelastic flow is normal to the yield surface.

1. Introduction

This paper analyses the initial yield behavior of gray cast iron materials with a lamellar shaped graphite microstructure (GJL). Because there are no strong chemical bonds between the metallic matrix and the graphite inclusions, their interface does not carry technical relevant forces under tensile loading. If gray cast iron materials are loaded to compression, forces can be transmitted across the graphite inclusions that leads to a more homogeneous stress distribution within the material. Hence, due to the characteristic microstructure, gray cast iron materials exhibit the features of a pressure dependent yield stress, dilatancy and tension–compression asymmetry.

The considered material class is often used to manufacture rather complex and well-priced components. Due to the characteristic physical quantities of a high damping and thermal conductance GJL is often used for cylinder heads or brake discs. The reduced load carrying capability under tension however, request a good understanding of the mechanical behavior, especially for safety relevant components.

Within the development process of components, efficiency and reliability are claimed so that numerical methods are used to find a proper design. Especially the finite-element method (FEM) is a powerful tool to analyze stresses and (plastic) strains within the components. To this end, appropriate material models together with the corresponding material properties must be applied to obtain realistic and meaningful results.

In the literature, many pressure-dependent continuum models from different scientific disciplines are proposed. A first insight can be found in the work of Aubertin and Li (2004). Therein, a yield criterion for porous materials is derived and compared to several pressure-dependent models from the literature.

With application to GJL, Josefson and Hjelm (1992) compared three different kind of yield functions. In contrast to the classical von Mises plasticity that bases only on the second invariant of stress deviator (J_2) the presented yield functions also depend on the first (I_1), second (I_2) and third (I_3) invariant of the stress tensor. Hjelm (1994) performed biaxial tests on GJL and investigated the initial yield surface under biaxial stress conditions. The comparison with one of the constitutive models presented in Josefson and Hjelm (1992) showed a good agreement. The used model contains two different yield functions that are exclusively active in dependence of the hydrostatic stress state. Another yield criterion developed for GJL in Altenbach and Tushtev (2001) and compared to the biaxial experiments of Hjelm (1994) depends on I_1, J_2 and J_3. Wiese and Dantzig (1990) constructed their yield surface by assembling four different yield functions of the respective octant in principal stress space and compared their approach with

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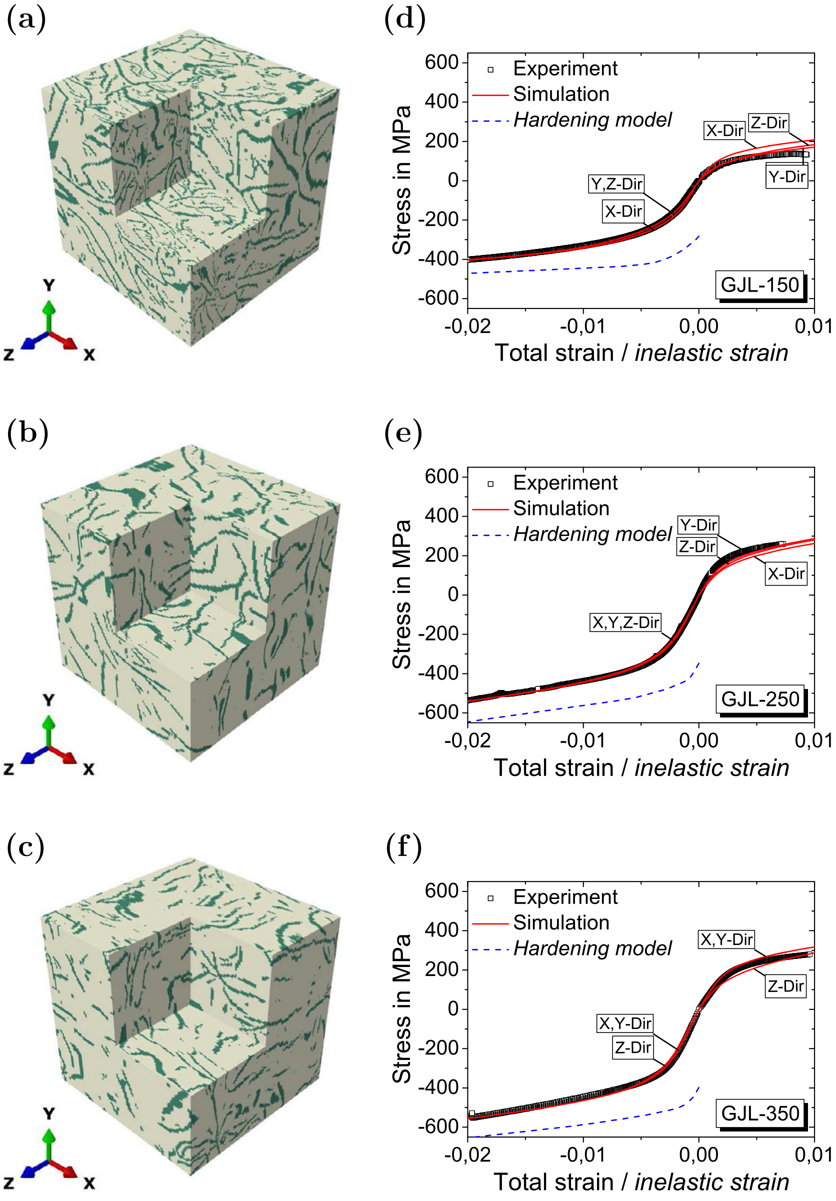

Fig. 1. Reconstructed VEs of Metzger and Seifert, 2014: (a) GJL-150, (b) GJL-250, (c) GJL-350, stress–strain curves: (d) GJL-150, (e) GJL-250, (f) GJL-350.

experimental investigations (given reference to the work of Coffin (1950)).

Seifert and Riedel (2010) presented a model that bases on the Gurson-type yield function in order to predict the cyclic stress–strain behavior of different cast iron materials with spherical, vermicular and lamellar graphite inclusions. Seifert and Schmidt (2009) found a good agreement in the stress response of a unit cell with one single pore with the presented modified Gurson model. While the model is reasonable for nodular cast iron, too high volume fractions are required to describe the tension–compression asymmetry for lamellar gray cast iron.

The cast iron plasticity model presented in the commercial finite-element software ABAQUS/Standard makes use of a composite yield surface to describe the different behavior in tension and compression. In tension yielding is governed by the maximum principal stress. Under compression yielding is pressure-independent and governed solely by the deviatoric stress state.

Besides the onset of yielding, reliable continuum models for GJL materials must also describe the inelastic flow direction properly. This is usually done by total differentiation of a flow potential for the current stress tensor. In what is called associative plasticity, the flow potential is equal to the yield function of the material model so that the direction of the inelastic flow is normal to the yield surface. In what is called non-associative plasticity, the flow potential differs from the yield function and thus the direction of the inelastic flow is not normal to the yield surface. Both approaches, associative and non-associative inelastic flow, are recommended for GJL in the literature. In e.g. Josefson and Hjelm (1992), Altenbach and Tushtev (2001) and Seifert and Riedel (2010) the inelastic flow is associated with the yield function, while the yield function and the flow potential differ in the ABAQUS/Standard gray cast iron model under hydrostatic tension.

In order to validate or develop reliable continuum models either experimental investigations or numerical simulations that include