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Computational assessment of the microstructure-dependent plasticity of lamellar gray cast iron – Part I: Methods and 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, 79108 Freiburg, Germany

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ABSTRACT

This paper focuses on the microstructure-dependent inelastic behavior of lamellar gray cast iron. It comprises the reconstruction of three dimensional volume elements by use of the serial sectioning method for the materials GJL-150, GJL-250 and GJL-350. The obtained volume elements are prepared for the numerical analyses by means of finite-element method. In the finite-element analysis, the metallic matrix is modeled with an elastic–plastic deformation law. The graphite inclusions are modeled nonlinear elastic with a decreasing value of Young's modulus for increasing tensile loading. Thus, the typical tension–compression asymmetry of this material class can be described. The stress–strain curves obtained with the microstructure-based finite-element models agree well with experimental curves of tension and compression tests. Besides the analysis of the whole volume element, the scatter of the stress–strain response in smaller statistical volume elements is investigated. Furthermore, numerical studies are performed to reduce computational costs.

1. Introduction

This paper focuses on the deformation behavior of gray cast iron materials with a lamellar shaped graphite microstructure. As a consequence of the weak interface between the metallic matrix and the graphite inclusions in tension and the load bearing capacity of graphite in compression, this material class typically exhibits the features of a pressure dependent yield stress, dilatancy and tension–compression asymmetry (see e.g. Wiese and Dantzig (1990) with reference to Walton and Opar (1981)).

In general, the mechanical properties of lamellar gray cast iron are worse than at those with a vermicular or spherical graphite shape. However, due to a high thermal conductivity along the graphite basal plane, the overall thermal conductivity increases with the amount of graphite and a more pronounced lamellar structure. Hence, gray cast iron materials with lamellar graphite inclusions might be preferred if components are subjected to thermo-mechanical loadings, although their mechanical properties are worse. Thus, e.g. cylinder heads or brake discs are often casted by this material class to reduce thermal gradients of such highly loaded components.

For the reliable and efficient design, numerical methods are often required, especially if the components are rather complex. The finite-element method (FEM) is a powerful tool to analyze stresses and (plastic) strains within the components and contributes to a better understanding of the overall mechanical behavior under some external loadings. The quality of the finite-element analysis however strongly depends on the reliability of the underlying material models. Hence, it is necessary to come up with appropriate models that describe the deformation behavior of the used materials as good as possible.

Several models have been proposed in the literature that are able to describe the characteristic tension–compression asymmetry of gray cast iron materials, see e.g. Wiese and Dantzig (1990), Josefson and Hjelm (1992), Hjelm (1994), Josefson et al. (1995), Altenbach et al. (2001), Altenbach and Tushtev (2001), Aubertin and Li (2004), Seifert and Riedel (2010), Metzger and Seifert (2013). The models contain material properties that are governed by the materials microstructure and that are usually determined on the basis of uniaxial experiments.

In Fig. 1 the stress–strain curves of uniaxial tension and compression tests are shown for the cast iron materials GJL-150, GJL-250 and GJL-350. Based on their nomenclature the materials

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* Corresponding author at: Offenburg University of Applied Sciences, Badstraße 24, 77652 Offenburg, Germany.

E-mail address: mario.metzger@hs-offenburg.de (M. Metzger).

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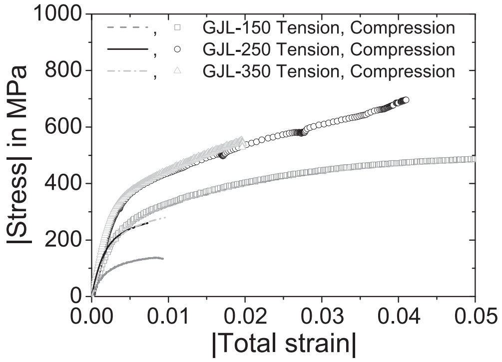

Fig. 1. Experimental stress–strain curves of the investigated materials.

should exhibit a uniaxial tensile strength at room temperature of 150, 250 and 350 MPa, respectively. The differences concerning the stiffness, strength and ductility between the respective materials in the tension–compression range is a consequence of the different microstructures that are shown in the etched micrographs in Fig. 2. The metallic matrix is primarily pearlitic with some single ferrite zones that mainly enclose the graphite precipitations. For GJL-150 more purely ferritic grains are found than in the other two materials (see white region in detailed Figure of GJL-150 with 20 μm length scale). According to the standard DIN EN ISO 945 the graphite flakes of the investigated materials lie within category 3 and 4.

Insights into effects of the microstructure on mechanical properties can be gained from numerical investigations. This requires the reconstruction of the materials microstructure and the preparation for numerical methods like the FEM or the Fast Fourier Transformation (FFT). Different approaches are presented in the literature for the reconstruction of a material's microstructure. Chawla et al. (2004, 2006) reconstructed the three-dimensional microstructure of SiC reinforced aluminum composites via a serial composition of subsequent micrographs and prepared the obtained volume elements (VE) for the numerical analysis with the FEM. Velichko et al. (2007) obtained the spherical, vermicular and lamellar graphite structure of gray cast iron by means of the Focused Ion Beam method. Micro computer tomography can also be used to determine the microstructure of a material, see e.g. Limodin et al. (2009, 2010).

The crucial point in the numerical analysis of VEs is their size in comparison to the microstructure characteristic length. Kanit et al. (2003) proposed a quantitative definition for the size of a VE in order to be representative in the case of linear elasticity. Amongst others, this quantity depends on the volume fraction of the individual components and the difference in their physical properties. Hill (1963) defines a volume to be representative if it is "entirely typical of the whole mixture on average and contains a sufficient number of inclusions for the apparent overall moduli to be effectively independent of the surface values of traction and displacement".

In the case of gray cast iron with lamellar graphite inclusions the aspect ratio (graphite flake length with respect to its thickness) can reach an order of more than 200, e.g. length of 1000 μm and thickness of 5 μm. This means, that the discretization in a numerical analysis must be "fine" enough to resolve the microstructure correctly and that the size of the VE must be "large" in order to obtain a RVE. Hence, the numerical requirements for the analysis of RVEs might exceed the machines capacity.

Instead of analyzing a RVE, statistical approaches can be used that operate on smaller VEs or more precisely their statistical volume elements (SVE), as suggested in e.g. Hohe and Becker (2005) and Hardenacke and Hohe (2009). Therein, the authors analyze substructures of two-dimensional model foams with an irregular microstructure under large macroscopic deformations. The benefit of their approach is that smaller VEs can be analyzed and that statistical information on the local deformation behavior is obtained from the SVEs.

In this work, VEs of GJL-150, GJL-250 and GJL-350 are reconstructed and their micro- and macromechanical material properties are determined by means of the FEM. It is intended to clarify how the two different phases, the metallic matrix and the graphite precipitations, can be modeled and to emphasize further necessary adjustments for a successful finite-element analysis of the boundary value problems. Following the approach of Hohe and Becker (2005) and Hardenacke and Hohe (2009), this paper furthermore analyses the mechanical response on SVE level. The macroscopic

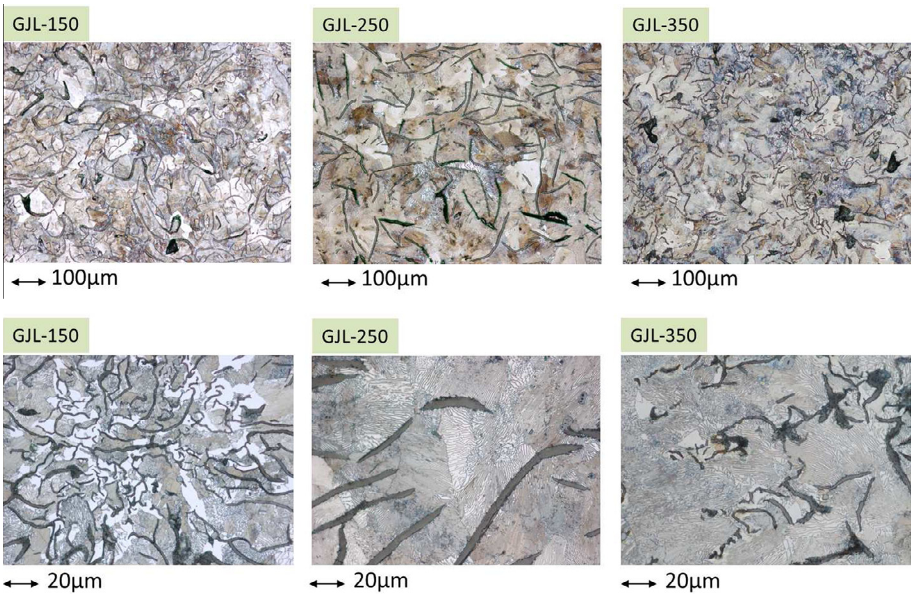

Fig. 2. Etched micrographs of the investigated materials.