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Effect of void arrangement on ductile damage mechanisms in nodular graphite cast iron: In situ 3D measurements

Ante Buljac[a,b], Lukas Helfen[c,d], François Hild[a], Thilo F. Morgeneyer[b,*]

[a] *Laboratoire de Mécanique et Technologie (LMT), ENS Paris-Saclay, CNRS, Université Paris-Saclay, 61 avenue du Président Wilson, 94235 Cachan, France*
[b] *MINES ParisTech, PSL Research University, Centre des Matériaux, CNRS UMR 7633, BP 87, 91003 Evry, France*
[c] *Institute for Photon Science and Synchrotron Radiation, Karlsruhe Institute of Technology (KIT), 76131 Karlsruhe, Germany*
[d] *European Synchrotron Radiation Facility (ESRF), 38043 Grenoble, France*

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A B S T R A C T

The effect of the arrangement of two artificial voids on void growth and coalescence mechanisms is studied in flat specimens made of nodular graphite cast iron via in situ 3D laminography imaging and digital volume correlation for bulk displacement measurement. Two configurations of machined holes are studied (i) 90° with respect to the loading direction to mimic internal necking, and (ii) 45° to attempt to trigger a void sheeting mechanism between the artificial voids. The machined holes play the role of primary voids, the graphite nodules that of secondary voids. At a lower scale there is a smaller third population of voids. The 45° void orientation successfully causes a shear band between the primary voids. However, the growth and coalescence mechanisms of voids from graphite nodules are similar for the two configurations. Internal necking is found for nodules that are close to each other and void sheeting for large ferrite ligaments between nodules. Strain fields in the region between machined holes show necking for both cases as well as volume increase, i.e., positive trace of the strain tensor, confirmed by image analysis. The strain to failure in this inter-void region is evaluated in the bulk and also locally, between nodules and for different coalescence configurations. Similar levels are observed in both cases.

1. Introduction and motivation

A whole range of engineering materials has been optimized throughout history following the idea of avoiding brittle fracture. This quest resulted in significant portion of modern materials failing in ductile manners. The constant quest for more fuel efficient and hence lighter design implies extended knowledge about the ductile damage mechanisms during forming and in-service conditions. Significant efforts in modelling of ductile failure processes have been made during the past few decades, which resulted in substantial progress of knowledge [4]. However, the full understanding of ductile failure mechanisms under specific stress states still remains an open question.

Low stress triaxialities (< 1) induce phenomena that cannot be handled with classical ductile damage models [17,32] that are tailored for higher triaxialities. Phenomenological approaches where the strain to failure ϵ_f is defined as a function of stress triaxiality η and Lode parameter μ [33,1,16,52] yield satisfactory results in industrial contexts but still without general applicability. There is no robust ductile damage model that is able to correctly predict fracture loci $\epsilon_f(\eta,\mu)$ under arbitrary loading paths [13,12]. It has been demonstrated in previous works that both damage growth [37] and strain to failure values [3] are loading path dependent, i.e.,

* Corresponding author.
E-mail address: thilo.morgeneyer@ensmp.fr (T.F. Morgeneyer).

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nonproportional loading conditions lead to different ϵ_f values for similar stress-averaged triaxialities.

The main reason for the above mentioned shortcomings is an incomplete understanding of ductile damage mechanisms. The lack of quantitative experimental data and their questionable interpretation result in case-sensitive model calibrations where the underlying physics is not fully captured.

3D imaging methods, e.g., Synchrotron Radiation Computed Tomography (SRCT) [22,21,23,29], allow for *in situ* monitoring of the three principal stages of ductile damage, namely nucleation, growth and coalescence of the voids at the microscale. While tomography is limited to scanning stick-like samples with small cross sectional areas, Synchrotron Radiation Computed Laminography (SRCL) [19,18,25,11,36,48] enables regions of interest (ROIs) in laterally extended objects to be scanned. In the context of mechanical experiments this feature facilitates performing *in situ* experiments with sheet- or panel-like samples [54,26] with more engineering relevant boundary conditions, different levels of stress triaxialities and significant sizes of plastic deformation zones. Digital Volume Correlation (DVC) can be employed to measure 3D bulk kinematic fields [43]. The measured displacement fields can be used for driving FE simulations that account for underlying microstructures [9,42]. The proposed method where the FE model accounts for the real microstructure and is driven by measured boundary conditions can be extended to inverse identification purposes at the microstructure level.

In this work *in situ* laminography experiments are performed on nodular graphite cast iron sheet samples that contain two machined holes. The geometry of the samples is inspired by the work of Weck et al. [51]. Two variants of the sample geometry will be studied, namely, (a) two holes are machined at 45°, (b) two holes are machined at 90° with respect to the loading direction. The general idea is to induce natural localization between the machined holes and observe whether there are any fundamental differences between damage mechanisms in the localized band for the two cases. The material itself contains two particle populations, namely, graphite nodules considered as voids because of their weak mechanical properties [15,53,6,20] and the population of small particles present in the ferritic matrix before loading. Hence, after machining holes with a diameter one order of magnitude higher than that of nodules, the proposed configuration presents a rather unique opportunity to observe three void populations in a single experiment.

The laminography technique enables us to focus on void growth in the sheet for the first time under such boundary conditions while DVC will be used for measuring the bulk kinematics. The estimated strain fields will be utilized for the determination of strains to failure for 90° and 45° configurations in the ligaments between the nodules and on the scale of the macroband between the machined holes. Void growth in the examined region and individual growth of the chosen voids will be reported by using segmentation technique on laminography images. Additionally, mean void growth measurements will be supported by analyzing the volumetric part of the strain tensor. Finally, measured meso- and micro-coalescence and fracture criteria in terms of both laminography and DVC kinematic data will be analyzed.

2. Experimental methods

2.1. Sample preparation

The studied material is a commercial nodular graphite cast iron with the serial code EN-GJS-400 [20]. The specimen geometry, which is shown in Fig. 1, is inspired by the work of Weck et al. [51]. The holes 500 μm in diameter have been machined by means of Electrical Discharge Machining (EDM). The nodules have a characteristic size of around 60 μm. Hence, they can be considered as distinct void populations with respect to the machined holes. In Ref. [51], the authors used machined holes of micrometer size. Consequently, the observation of the secondary void population was very limited due to the current imaging technique resolution [44]. Conversely, the larger size of the holes and graphite nodules in this work shall allow for such observations. Furthermore, the initial small graphite fragments in the ferritic matrix (< 1 μm) can also be detected in laminography scans, therefore they are

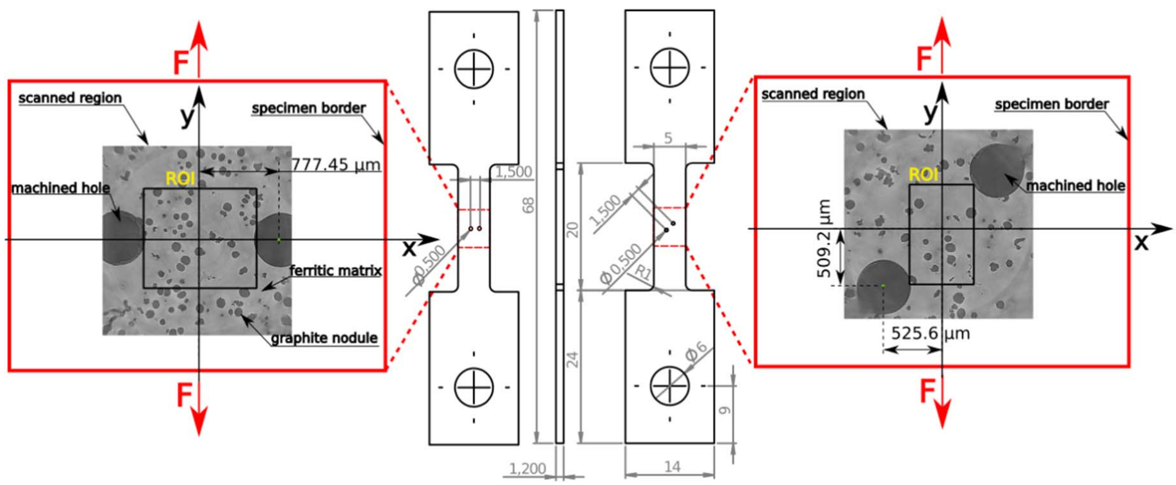

Fig. 1. Drawings of the two samples with the scanned regions and the regions of interest (ROIs) for DVC analyses.