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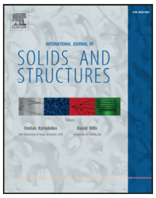

Void growth and coalescence in a three-dimensional non-periodic void cluster

Victor Manuel Trejo Navas*, Marc Bernacki, Pierre-Olivier Bouchard

Mines-ParisTech, PSL-Research University, CEMEF Centre de mise en forme des matriaux, CNRS UMR 7635, CS 10207 rue Claude Daunesse, Sophia Antipolis Cedex 06904, France

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ABSTRACT

Void growth and coalescence are studied in this work through Finite Element simulations. A methodology for the study of three-dimensional non-periodic configurations is proposed. In order to avoid the hypothesis of microstructural periodicity, a three-dimensional cluster with three initially spherical voids, is modeled. Multiple spatial configurations are simulated in a parametric study. The pre-coalescence behavior is detailed through the evolution of the volume of each void, the minimum intervoid distance, and the equivalent plastic strain in the middle of the shortest path between voids, and the resulting coalescence mechanism is described. Locally accelerated and non-homogeneous void growth is observed close to the localization band. Although only coalescence by internal necking is present, apparent void-sheet formation is observed if only a two-dimensional slice is considered. These observations, and a comparison with the Rice–Tracey growth model, highlight the importance of fully considering the three-dimensional complexity of the ductile damage micromechanisms.

1. Introduction

A better understanding of ductile damage can enhance the accuracy of fracture prediction during in-use life, optimize designs of mechanical pieces, and improve forming processes. Further improving the understanding of the micromechanisms of ductile damage -void nucleation, growth, and coalescence- is essential for the development of more predictive and universal macroscopic models. This paper focuses on void growth and on void coalescence mechanisms.

Void coalescence is usually categorized into three different mechanisms (Pineau et al., 2016; Benzerga and Leblond, 2010). The first and most common mechanism is coalescence by internal necking of the intervoid ligament. In the second mechanism, two voids seemingly wide apart, are suddenly united by a narrow void sheet. This is referred to as void-sheet mechanism. The third and less common mechanism is known as necklace coalescence or coalescence in columns, in which voids link up along their length.

Void-sheet coalescence was observed by Cox and Low (1974) in an AISI 4350 alloy (see Fig. 1). The authors identified these void sheets as planar features formed by small voids, and oriented at 45° with respect to the tensile axis. The orientation of this feature coincides with the direction of maximum shear. This void-sheet mechanism can have a negative impact on the ductility of the material (Cox and Low, 1974; Goto et al., 1999).

Recent efforts have employed three-dimensional imaging techniques, such as X-ray tomography or Synchrotron radiation computing tomography (SRCT), to study and improve the understanding of ductile damage mechanisms (Gammage et al., 2005; Weck et al., 2008; Maire et al., 2011; Shen et al., 2013).

Babout et al. (2004) studied damage in model metallic materials via X-ray tomography by carrying out in situ tensile tests in two different aluminum matrices reinforced with spherical hard ceramic particles. The authors observed coalescence (Fig. 2) in the highest strained regions between voids at approximately 45° from the tensile direction.

In the analysis of SRCT images of a commercial nodular graphite cast iron (EN-GJS-400) (Buljac et al., 2017; Shakoor et al., 2017b), various instances of apparent void-sheet coalescence have been observed. Two examples of these instances are presented in Fig. 3. The tensile direction corresponds to the vertical direction. The specimen presents two holes created via Electrical Discharge Machining (EDM) to favor shear conditions between the holes. Two coalescence instances are indicated in red in Fig. 3(b). Even though the two-dimensional images suggest the occurrence of the void-sheet mechanism, the three-dimensional images hint at a possible intervention of voids located close to the observed coalescence; the objective of this work is to numerically investigate the possible intervention of neighboring voids. More details on damage and

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* Corresponding author.
E-mail address: victor-manuel.trejo_navas@mines-paristech.fr (V.M. Trejo Navas).

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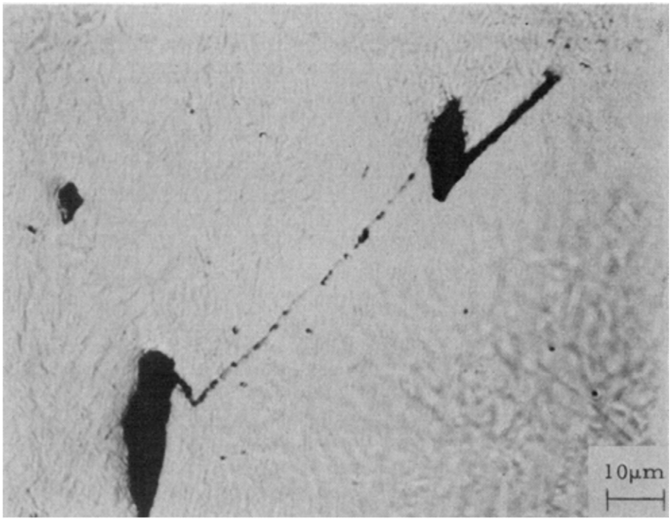


Fig. 1. Instance of void-sheet mechanism observed by Cox and Low (1974) in an AISI 4350 alloy.

failure mechanisms of this material can be found in the works of Buljac et al. (2018).

To investigate three-dimensional effects on the apparent void-sheet mechanisms observed in different materials, Finite element (FE) simulations are carried out. A three-dimensional non-periodic cluster of three voids is investigated in a parametric study. Since a classical unit-cell approach is not suitable for this task, a methodology for the study of three-dimensional non-periodic clusters of voids and/or particles is proposed. In Section 2, the numerical framework, the proposed methodology and the parametric study are described. Results are presented and discussed in Section 3, and conclusions are drawn in Section 4.

2. Methodology

2.1. Numerical framework

Since the used numerical framework has been sufficiently documented in previous publications (Shakoor et al., 2015a; 2017a), only a brief description is given here.

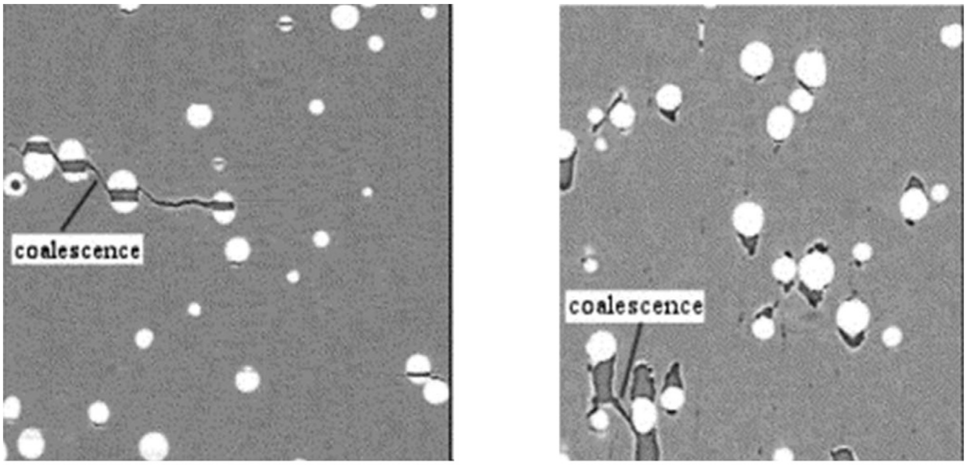
The multiphase FE simulations are carried out with a Lagrangian formulation and a monolithic approach, i.e., on a single mesh. The void-matrix interface is described by the zero isovalue of a distance function. The distance function is convected with the Lagrangian mesh motion and, when necessary, reinitialized with an efficient and parallel algorithm (Shakoor et al., 2015b). Body-fitted meshing and remeshing operations are performed when necessary with an excellent conservation of the void phase (Shakoor et al., 2017a). The way in which coalescence is handled in the FE mesh, has been treated in detail in previous work (Shakoor et al., 2017a). The matrix is considered elasto-perfectly plastic (Young's modulus $E = 210000$ MPa, Poisson's ratio $\nu = 0.3$ and yield stress $\sigma_y = 290$ Mpa) and the void phase is modeled as a compressible Newtonian fluid (viscosity $\eta = 2.1$ MPa s^{-1}); this approach has been previously validated (Roux et al., 2013). A mixed velocity/pressure formulation with a P1+/P1 element is used (Brezzi et al., 2008). Sensitivity analyses with respect to the temporal and spatial discretizations were carried out in order to find optimal parameters in terms of precision and numerical cost. As in the work of Roux et al. (2013), an additional sensitivity analysis was carried out to verify that the mechanical properties of the void phase, and the resulting internal pressure in the voids, bears no influence on the considered observables.

2.2. Methodology for the study of void and/or inclusion clusters

2.2.1. Motivation

The unit-cell approach (Needleman, 1972; Tvergaard, 1981) has been very important in the development of the local approach to fracture. A great number of studies have been and continue to be carried out with this approach. Typically, in the unit-cell approach, a single inclusion or void is embedded in a unit-cell surrounded by periodic boundary conditions. This greatly simplifies the study of the micromechanisms of ductile damage and allows the effect of many microstructural variables to be assessed. Doing so, however, imposes an important simplifying hypothesis: that the studied microstructure can be represented by a periodic arrangement of microstructural features.

The hypothesis of a periodic microstructure is not always an appropriate approximation. This constitutes a compelling reason to enrich the available tools and methodologies for the study of ductile damage. Within the unit-cell framework, different works have extended the original framework by considering unit-cells with multiple voids/particles. Thomson et al. (1998) studied the effect of the orientation of a particle cluster with respect to the main loading direction, on void nucleation and growth. The study was



(a) Hard matrix (b) Soft matrix

Fig. 2. Coalescence instances observed by Babout et al. (2004). Figures adapted from Babout et al. (2004).

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