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A level-set and anisotropic adaptive remeshing strategy for the modeling of void growth under large plastic strain

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ABSTRACT

A numerical model based on the use of a level set framework coupled with an anisotropic re-meshing technique is presented in order to describe the void growth process for 2D and 3D configurations. Interfaces of inclusions and voids are described implicitly using level set functions. An anisotropic meshing – remeshing strategy is employed to track interfaces and ensure the accuracy of finite element calculations. The matrix and inclusions are elastic–plastic materials. The numerical methodology is adopted to study the effect of different parameters such as void or inclusion orientation and domain size. A good agreement is found with available experimental data and those found in the literature. The proposed method is shown to be an efficient promising technique to study ductile damage stages as void nucleation and growth. A demonstration of the method potential is illustrated by studying void growth for a 2D real complex microstructure and for a simple 3D microstructure.

1. Introduction

Ductile damage usually involves the nucleation, growth and coalescence of voids in a plastically deforming material [1]. In many structural alloys, especially steels, void nucleation occurs in preferential sites in the neighborhood of secondary particles. Void nucleation occurs either by inclusions fracture, or by particles-matrix interfaces debonding. The preferential mechanism of void nucleation depends on several parameters such as matrix and inclusions fracture properties, interface properties and the nature of loading [2,3]. The second ductile damage mechanism is void growth, which is related to the increase of plastic strain around the nucleated voids. Finally, for large plastic strain, and when voids are close to each other, the coalescence phenomenon occurs and finally leads to the appearance of macroscopic cracks.

Several studies have been undertaken to model the ductile damage process at the macroscale. Two main approaches can be distinguished: phenomenological continuum models, such as the Lemaitre model [4] and microscopically based models such as the model initially defined by Gurson [5] and then extended by Tvergaard and Needleman [6]. Phenomenological models do not take into account the micro-mechanisms of ductile damage, whereas the Gurson–Tvergaard–Needleman (GTN) model comes from micromechanics-based considerations of plastic behavior within the framework of porous metal plasticity. Several extensions of the GTN model were developed in order to incorporate void shape effects, and plastic anisotropy. The GTN model is based on the definition of laws for void nucleation, growth and coalescence but it still remains a macroscopic approach since it does not track explicitly void evolution.

With the development of the Finite Element Method (FEM) and the improvement of calculation capabilities, a new approach to model the micro-mechanisms of ductile damage was developed. This approach aims at modeling void nucleation, growth and coalescence explicitly and tries to draw up the void evolution in the neighborhood of inclusions. This kind of approach was initially proposed by Needleman [7] and Tvergaard [8] who worked on regular cylindrical void arrangement in 2D. These approaches on unit-cell were next extended in 3D [9,10]. These works were clearly pioneer and many studies have since followed. Several studies were carried out in order to model void nucleation by considering a Cohesive Zone Method (CZM) [11–14]. Li and Ghosh [11] modeled the interfacial debonding in fiber reinforced composites using such a technique. McVeigh and co-workers [14] also used this numerical method to explain the mechanisms of nucleation of voids around particles in a Representative Elementary Volume (REV) subjected to shear loading. In other studies, the mechanisms of void growth and coalescence were treated [15–17]. Bandstra et al. [15,16] studied the deformation localization for void arrays, based on experimentally observed inclusion microstructures of steels. The effect of temperature on void growth was examined by Horstemeyer et al. [17]. The growth and coalescence of voids after nucleation were treated by McVeigh [14]. His model is based

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on the use of a REV containing particles under shear loading. In most of these studies, the classical FEM is employed to analyze strain/stress concentrations, inclusion orientations and shape effects, and inclusion distribution effects.

Several new finite element techniques were developed more recently to model moving discontinuities (interfaces, cracks) without remeshing. Among these methods, the eXtended Finite Element Method (X-FEM) [18–21] is probably one of the most recognized approaches to deal with discontinuities. This method consists in enriching elements that are crossed by the discontinuity (cracks or interfaces). The discontinuity is described by a level set function. Level Set Methods (LSMs) [18–27] were initially presented by Osher and Sethian [22] and described in more details by Sethian [23]. The principle of the method is to represent implicitly an interface by the zero level of a function, called the level set function. In the X-FEM approach, the finite element approximation space is enriched by appropriate functions through the concept of partition of unity. Thus, material interfaces do not need to be aligned with element edges but can intersect the elements arbitrarily while the accuracy of the finite element approach is retained. The use of level set functions in the X-FEM framework gave rise to numerous publications dealing with the modeling of discontinuities in ductile and brittle fracture [18–21]. Moës and co-workers [18] modeled crack growth without remeshing and Hettich and co-workers [20] analyzed interface material failure. The combination of X-FEM with LSM is also a convenient way to model material discontinuity at the micro-scale [19–24,25]: Sukumar et al. [19] modeled voids and inclusions using a combination between LSM and X-FEM, Legrain [24] and Hiriyur et al. [25] have studied REV homogenization using real or statistical REV.

The use of enrichment in the X-FEM approach was made initially to avoid remeshing. Indeed remeshing can become an issue when dealing with 2D or 3D complex geometries and large strain. In recent studies [26], the X-FEM framework is applied for large plastic strain, but without remeshing. However, when large strain occurs, some elements get distorted, giving rise to poor finite element accuracy. Automatic remeshing is a useful way to preserve elements quality in such configurations.

The method presented in this paper is also based on LSM method but, contrary to X-FEM, discontinuities are tracked using anisotropic mesh adaptation. This approach is particularly well suited to deal with large strains.

In this paper, an enhanced anisotropic remeshing procedure is used. This mesh adaptation is employed in a very efficient way to capture inclusions' and voids' interfaces which are described using level set functions. These interfaces are tracked accurately all along the simulation of void growth thanks to automatic anisotropic meshing adaptation. In addition, the geometric mesh adaptation around inclusions' and voids' interfaces is combined to a mesh adaptation based on computed mechanical fields. This method is shown to be effective in modeling void growth in an elastic–plastic media. In Section 2, the finite element model and the remeshing strategy are detailed. Numerical results are presented in Section 3. The model is first validated on a simple configuration. The influence of inclusions' configurations on void growth is then addressed in more details. Then, in order to illustrate the potential of the method, an application based on a real Scanning Electron Microscopy (SEM) picture is shown. Finally, a 3D configuration is presented to illustrate the ability of our framework to deal with 3D microstructures.

It is important to underline that in the present study, nucleation of voids due to inclusion/matrix debonding or inclusions' fracture will not be modeled. Voids are already existing in the initial configuration of the microstructure; only the growth mechanism will be simulated. In this context, a classical multi-domain finite element framework could be used. In fact a model based on an explicit description of the matrix and the inclusions, coupled with the proposed meshing–remeshing technique, without accounting for the void part could be envisaged. This approach would require the use of one mesh for each domain and the introduction of contact conditions. However, the strategy described here is a part of a larger goal, consisting in modeling the three natural stages of ductile damage using the same formalism. In this purpose, a precise modeling of topological events due to debonding or inclusions' fracture could not be envisaged in a classical multi-domain finite element formulation. The validation of the mechanical resolution methodology and of the meshing strategy of this global framework is presented in the present document whereas the introduction of a void nucleation criterion and a coalescence criterion, will be detailed in a forthcoming publication.

2. Finite element model and remeshing strategy

In the present work, a level set framework is used to model particles' and voids' interfaces. The initial FE mesh, independent of the different phases, is coarse and isotropic. This initial mesh will be anisotropically adapted to describe accurately the geometry of the domains (matrix, inclusions, voids) and to deal with discontinuities in material properties. This is an implicit description of heterogeneities.

2.1. Level set framework

Interfaces (particles and matrix interfaces) are implicitly described thanks to a level set framework as in [27–30]. In fact, the set of particles and the matrix are described, respectively, by a signed distance function, ϕ_i and ϕ_m, defined over the domain Ω which gives at any node x of the finite element mesh the distance to the corresponding interface (Γ_t and Γ_m). Furthermore, the sign convention $\phi_t \geqslant 0$ (resp. $\phi_m \geqslant 0$) inside the part of the domain corresponding to the inclusions denoted Ω_i (resp. inside the part of the domain corresponding to the matrix denoted Ω_m), and $\phi_i \leqslant 0$ (resp. $\phi_m \leqslant 0$) outside the inclusions (resp. outside the matrix) is adopted. In turn, both types of interfaces are given by the zero level of the corresponding distance function:

$$\begin{cases} \varphi_i(x) = (\chi_{\Omega_i}(x) - \chi_{\bar{\Omega}_i}(x))d(x,\Gamma_i), \varphi_m(x) = (\chi_{\Omega_m}(x) - \chi_{\bar{\Omega}_m}(x))d(x,\Gamma_m), x \in \Omega \\ \Gamma_i = \partial\Omega_i = \{x \in \Omega / \varphi_i(x) = 0\} \\ \Gamma_m = \partial\Omega_m = \{x \in \Omega / \varphi_m(x) = 0\} \end{cases} \tag{1}$$

where $d(x,\Gamma)$ defines the distance between node x and interface Γ and $\chi_D(x)$ corresponds to the characteristic function of the domain D.

As the set of the different phases correspond to a partition of the domain, it is easy to determine to which phase each finite element nodes belongs using the following rules:

$$\begin{cases} x \in \Omega_i \Longleftrightarrow \varphi_i(x) \geqslant 0 \\ x \in \Omega_m \Longleftrightarrow \varphi_m(x) \geqslant 0 \\ x \in \Omega_v(\textit{void part of the domain}) \Longleftrightarrow \varphi_v(x) = -\max(\varphi_i(x), \varphi_m(x)) \geqslant 0 \end{cases} \tag{2}$$

where ϕv defines the void interfaces.

The level-set functions are computed at nodes, a linear interpolation is used for the transport step between each remeshing operation. The level-set functions are transported with the lagrangian deformation of the mesh. This lagrangian deformation of the mesh does not keep the distance properties of the initial level set function (i.e. the gradient value of the level set function remains not equal to one during the deformation).

If this deviation is not an issue to determine the material phase (Eq. (2) does not require the evaluation of the distance values), it is