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Ductile fracture of a metal matrix composite studied using 3D numerical modeling of void nucleation and coalescence

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ABSTRACT

A finite element analysis of large 3D microstructures of randomly distributed particles is proposed to investigate the influence of particle debonding and fragmentation on void coalescence. This analysis is possible thanks to recent developments in parallel automatic remeshing techniques tailored for simulations of microstructures undergoing large deformations. These techniques are extended herein to model void nucleation by particle debonding and fragmentation. Micromechanical simulations of a model material with 20% particle volume fraction show that void nucleation leads to an early plastic strain localization micromechanism that favors void coalescence and reduces ductility significantly.

1. Introduction

Among recent efforts in materials science, the development of more predictive and general constitutive models based on micromechanical criteria has gained an increasing interest. Thanks to progresses in experimental means, the *in situ* observation of ductile fracture's void nucleation, growth and coalescence phenomena in full 3D is now possible [1–5]. Incorporating these observed micromechanisms into constitutive models requires a thorough analytical and/or numerical analysis and comparisons with experiments [6,7]. However, both analytical and computational models do not yet address conditions that are fully comparable to what is observed in experiments.

Very restrictive assumptions of a single spherical void embedded in a perfectly plastic von Mises matrix under specific loading conditions were used by Gurson in his well-known fundamental work [8]. Many analytical developments have generalized Gurson's yield criterion to an ellipsoidal void shape and more general loading conditions [9–12], and to complex matrix behavior [13,14]. Similarly, some FE analysis studies have considered microstructures consisting of a single void, or a periodic array of voids [15–18]. However, metal alloys feature particles and considering them as voids means neglecting their effect on the load carrying capacity, and the influence of void nucleation mechanisms. The influence of the particles and their debonding from the matrix has been considered in Refs. [19–21], with a restriction to periodic arrays of particles. The competition between particle debonding and fragmentation for these periodic arrangements is neglected in most studies, with the exception of Ref. [21]. Idealized microstructures such as periodic arrays of voids or particles are not representative of real ductile materials, which feature random arrangements of voids and particles. Random arrangements of particles with

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a debonding model have been addressed in Ref. [22], while a fragmentation model has been used in Ref. [23]. Random arrangements of voids have also been considered in the literature [24,25].

In spite of this substantial literature, a number of assumptions still have to be investigated. The number of particles modeled in most 3D FE analysis studies is generally not large enough to statistically represent the random distribution of particles found in real materials [26,27]. The competition between the two void nucleation mechanisms of particle debonding and fragmentation, and their interaction with void coalescence at large plastic strains have not been investigated yet for large and random 3D arrangements [7]. There is definitely an interest for a parallel numerical framework enabling for simulations of large 3D microstructures with a representative number of randomly distributed particles [27], as well as for numerical methods that can be used to model particle debonding and fragmentation, and void coalescence [21]. An attempt to develop such framework has been proposed in a previous work by the authors, and successfully applied to the 2D full field modeling of a representative number of randomly distributed voids [28,29] and particles [30]. Particle debonding and fragmentation criteria were introduced [30], as well as a void coalescence criterion [29]. These developments nevertheless suffered from several limitations that did not enable for large scale 3D simulations.

In this paper, these limitations are addressed thanks to recent numerical developments. Then, a FE micromechanical analysis is proposed that accounts for both particle debonding and fragmentation, and the growth and coalescence of the nucleated voids, at large plastic strains and for large 3D microstructures. The main objective of this analysis is to show the relevance of a simultaneous modeling of both void nucleation and coalescence, and to reveal interactions between these two phenomena, with a major influence on ductility.

The existing numerical framework is described in Section 2, while new methods and micromechanical models introduced for the purpose of the present analysis are presented in Section 3. This improved FE analysis tool is then applied to show the influence of void nucleation on localization and void coalescence in Section 4.

2. Numerical framework

2.1. Constitutive modeling

The domain is a 2D or 3D Representative Volume Element (RVE) generally composed of a matrix, particles, and voids. In the present framework all phases are meshed, with the use of a conform FE meshing strategy at boundaries between different phases. A particularity of the present framework is that voids are also meshed, meaning that there are mesh elements inside cracks. These elements are only used for remeshing purposes, and measurement of void volume fraction, but have no stiffness or constitutive behavior. Their effect is hence no different than actual voids (that would not be meshed).

Hooke's law is used to model elasticity in both matrix and particles. In addition, a von Mises yield criterion is used for the matrix, with power hardening law [31]

$$\sigma_0(\bar{\varepsilon}) = \sigma_y + K(\bar{\varepsilon})^n \tag{1}$$

where $\bar{\varepsilon}$ is the equivalent (von Mises) plastic strain, σ_y the yield stress, K the plastic consistency and n the hardening exponent. Particles are considered elastic brittle and hence assumed to debond or fragment before yielding can occur [32,23,20,22]. Fracture criteria are detailed in Section 3.

To reach large strains, an updated Lagrangian formulation is used where a static load is applied progressively using small increments. Each increment consists in solving continuum mechanics equations and then applying the computed displacements to move mesh nodes. Because of incompressible plastic behavior in the matrix, and the use of triangular (2D) and tetrahedral (3D) elements, a mixed velocity-pressure formulation solved using a $P1^+/P1$ element is adopted to avoid locking [33]. The nonlinearity of this formulation, due to the plastic behavior of the matrix, is solved implicitly using a Newton-Raphson scheme [34].

2.2. Mesh motion and adaption

The key aspects of the present framework are linked to remeshing and the mesh motion step that is applied at the end of each load increment. These algorithms enable for simulations featuring large void growth ratios and complex topological events such as void coalescence. The mesh motion algorithm first tries to move mesh nodes to their *final* positions by applying the computed displacement directly. If element flipping is detected (by computing element volumes), nodes are moved back to *intermediary* positions by dividing the displacement by two. This subdivision is applied recursively until the displacement is small enough so that no flipping is detected [35]. Remeshing is then operated with the expectation that the new mesh will render a motion towards *final* positions possible. If not, the same procedure is applied again until *final* positions are reached.

Both this mesh motion and the mesh adaption algorithm used at each motion iteration were introduced in previous works [36,29,35], and are hence only summarized herein. The main properties of the mesh adaption algorithm are that:

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